

Progress on FFAG Accelerators -towards Neutrino Factory

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- 2. FFAG - outlines*
- 3. R&D of FFAG proton model at KEK*
- 4. FFAG based Neutrino Factory*
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Needs for large beam power & rapid acceleration

1. Large Beam Power

Proton Driver:

secondary particle production ($K, \mu, \pi, n, RI, \dots$)

spallation neutron source

ADS for nuclear energy breeding

2. Rapid Acceleration

Acceleration of short-lived particles:

muon --- Neutrino Factory, Muon Collider

unstable nuclei

ENERGY: $1 \sim 10 \text{ GeV}$, CURRENT: $\sim \text{mA}$

Circular Accelerator

Synchrotron:

- * *Strong Focusing in 3D directions(trans. & long.).
Betatron and Synchrotron Oscillations.*
- > *Stable beam acceleration*

but, B is time-varying to keep a closed orbit constant.

- > *Duty Factor : small ~1%(rep. rate:~10Hz)
Small beam power compared with other cw
or semi-cw machines.*

Fixed B -----> Fixed Field Alternating Gradient(FFAG)

FFAG accelerator

**FFAG principle : Ohkawa (1953), Symon, Kolomensky
~'50s**

**Magnetic field strength : constant ---> Moving orbit
@MURA project**

- (1) proof-of-principle machine : electron model -> worked successfully!
- (2) 30GeV proton machine : proposal
- (3) proton-proton collider (two beam accelerator) : proposal

No practical machine so far!

- (1) Relatively large at high energy ($>30\text{GeV}$) : Big Magnet
- (2) Complicated magnetic field configuration : 3D design
- (3) RF cavity : Large beam aperture : Variable Frequency & High Gradient.

Cardinal Conditions of FFAG

Magnetic field configuration

* *Zero-chromaticity*

---> *Betatron functions are scaling for energy..: v_x, v_y constant*

$$x'' + g_x = 0; g_x = \frac{K^2}{K_0^2}(1-n)$$

$$z'' + g_z z = 0; g_z = \frac{K^2}{K_0^2}n$$

a) Geometrical similarity

$$\left. \frac{\partial}{\partial p} \left(\frac{K}{K_0} \right) \right|_{\theta=const.} = 0$$

b) Constant n

$$\left. \frac{\partial n}{\partial p} \right|_{\theta=const.} = 0$$

FFAG Magnetic Field Configuration

Scaling type of FFAG

a) Geometrical similarity b) Constant n

$$(a) \quad r \left(\frac{\partial \theta}{\partial r} \right)_\vartheta = \varsigma = \text{const.}, \quad (b) \quad n_\Gamma = - \frac{r}{B} \left(\frac{\partial B}{\partial r} \right)_\theta$$

$$B(r, \theta) = B_i \left(\frac{r_i}{r} \right)^{n_0} F \left(\theta - \varsigma \ln \frac{r}{r_i} \right)$$

Magnetic Field Configuration : Scaling Type

*a) Radial Sector
/tunable
/short straight section*

*b) Spiral Sector
/small excursion
/less tunable*

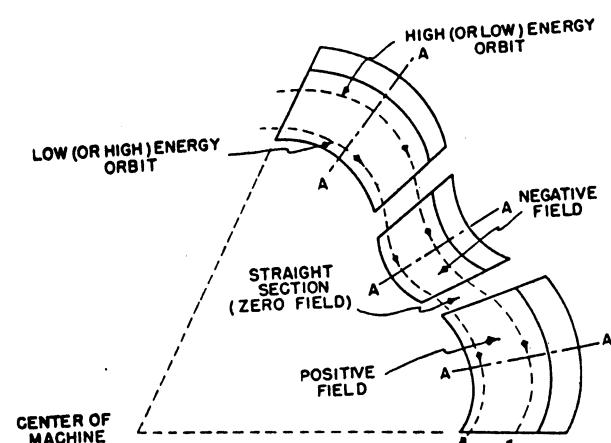


FIG. 2. Plan view of radial-sector magnets.

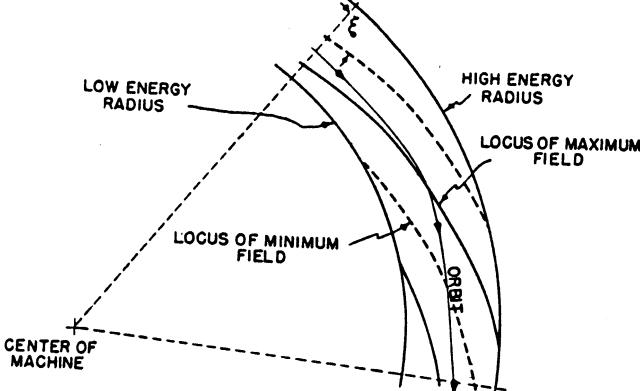


FIG. 3. Spiral-sector configuration.

Magnetic Field Configuration : Scaling Type

Orbit Excursion :

$$\Delta R \cong \left[\left(\frac{B}{B_0} \right)^{1/k} - 1 \right] R_0$$

K : Large (>>1) --> Orbit excursion ~ small

Large non-linear field for large K --> “Dynamic Aperture”

$$B \propto r^k = r_0 \left[1 + k\Delta r + \frac{k(k-1)}{2!} \Delta r^2 + \frac{k(k-1)(k-2)}{3!} \Delta r^3 + \dots \right]$$

FFAG: revival '80~'90

Spallation Neutron Source

*ESS(European Spallation Neutron Source) : ANL, Ullrich

*GEMINI : KEK

Medium energy $1\sim 3\text{GeV}$

High intensity $0.1 \sim 1\text{mA}$

(1) Large magnet : medium energy OK

(2) Magnet configuration : 3D code (TOSCA etc.) OK

(3) RF cavity : NO

FFAG Accelerator

Fast Facility for Accelerating Accelerators

Comparison with ordinary synchrotron

	FFAG	ord. Synchrotron
1. Magnetic Field	Static (Fixed)	Time varying
2. Closed Orbit	Moving	Fixed
3. Focusing	Strong	Strong
4. Duty Factor (Repetition Cycle)	Large ~10-50% (~>1kHz)	Small ~1 % (~10Hz)
5. Space charge/Instability	Not critical	Severe (small particle numbers per bunch)

Problems to be solved:

- * complicated magnetic field ---> 3D codes(TOSCA etc.)
- * RF system : **high field & rapid tuning**
---> “ High Gradient & Broad Band RF Cavity”

FFAG : revival again 2000

New type RF Cavity @KEK

“High Gradient & Broad band” ($f \sim \text{MHz}$)

“Magnetic Alloy (MA) loaded Cavity”

MA tape : “FINEMET”(nano-crystal alloy)

*High gradient : $50 \sim 100 \text{ kV/m}$ (ferrite $\sim 10\text{kV/m}$)

*Broad band : no need for frequency tuning($Q \sim 1$)

Large Repetition Rate : $\sim 1\text{kHz}$

Large beam aperture : MA tape

RF System

High Intensity & Medium Energy PS

**large ring radius*

**rapid cycling*

----> **large RF accelerating voltage**

Effective RF Field Gradient (RF Voltage per Length)

----> **as high as possible**

**total length of the RF cavities becomes short.*

**Impedance seen by the beam becomes small.*

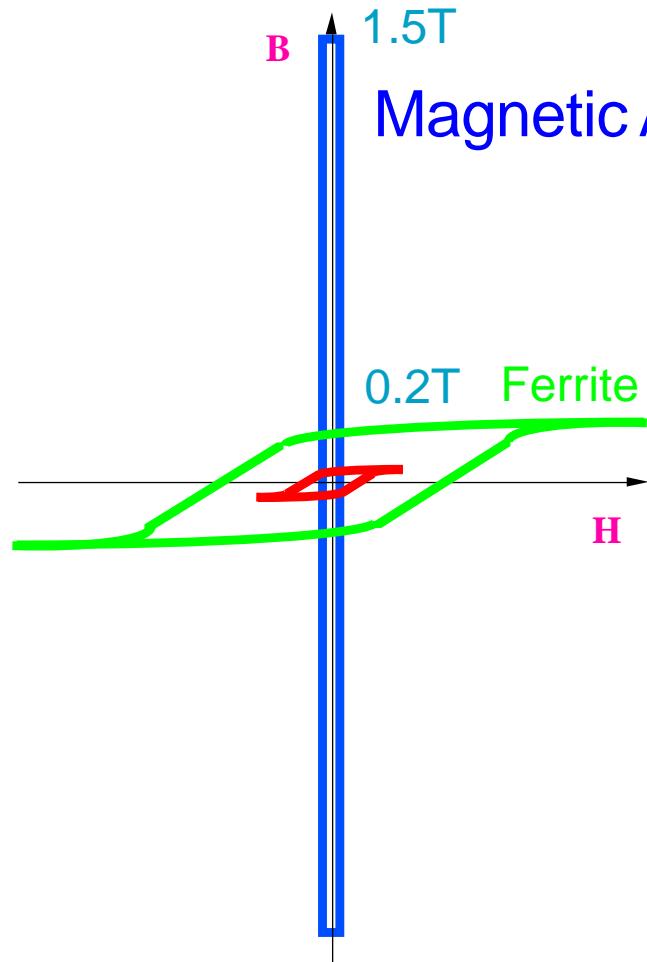
Problems of Ferrite-loaded RF cavity

Problems:

- a) μQf -value (\approx shunt impedance per unit length), decreases along with the RF magnetic field strength(Brf).
nonlinear hysteresis loss \rightarrow Brf : small
- b) Low Curie temperature, which is typically 100-200°C,limits use at high RF field gradients. \rightarrow low power density
- c) High loss effect at the static magnetic field limits use at a high RF magnetic field.
- d) Cavity with the high Q-value ferrite may excite the longitudinal coupled-bunch instability through a de-tuning process for curing high beam loading or in the parasitic mode.

“Low field gradient & Narrow band”

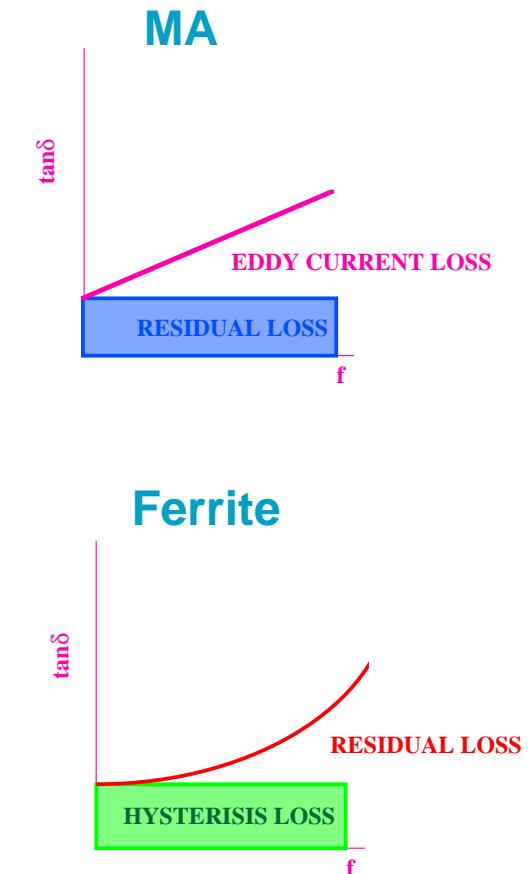
RF loss ($f=1\sim 10\text{MHz}$)



Magnetic Alloy:
thin tape($t\sim 10\text{mm}$)
(1)Eddy current loss
(2)Residual loss

Ferrite:
(1)Hysterisis loss
(2)Residual loss

→ **limit B_{rf}**

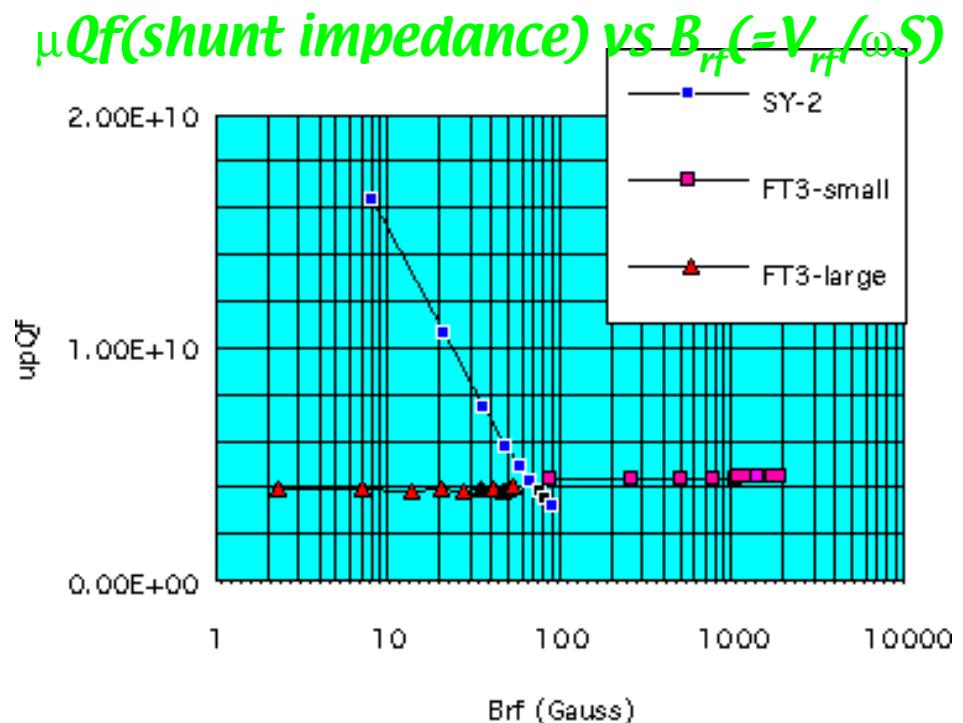


Magnetic Alloy

A high-permeability soft magnetic alloy, such as FINEMET and METGLAS has become available for applying the RF cavity, recently.

Characteristics of MA:

- (1) The μQf -value remains constant at a high RF magnetic field (B_{rf}) of more than 2 kG.
- (2) A high Curie temperature, typically 570°C for FINEMET.
- (3) The intrinsic Q-value is small. No frequency tuning loop is necessary in the cavity control system because of its low Q-value ($Q \sim 1$). This substantially widens the stable operating region of the cavity loading phase angle under heavy beam loading. The longitudinal coupled-bunch instability may be reduced
- (4) The Q-value can be increased up to more than 10 ($Q > 10$) by a radial gap with cut-core configuration.
- (5) Fabrication of a large core is possible because the core is formed by winding the very thin tapes.



Typical characteristics of Ni-Zn ferrite and Magnetic Alloy(FINEMET).

Power Density vs. Effective Field Gradient

Average power density for a toroidal core is given by

$$\bar{\rho} = \frac{W_L}{V} = \frac{2}{4\pi\mu\mu_0 Q f (r_o^2 - r_i^2) \times \ln\left(\frac{r_o}{r_i}\right)} \times \left(\frac{V_{rf}}{l}\right)^2$$

,

where $\left(\frac{V_{rf}}{l}\right)$ is an Effective Field Gradient(EFG).

a) Ferrite

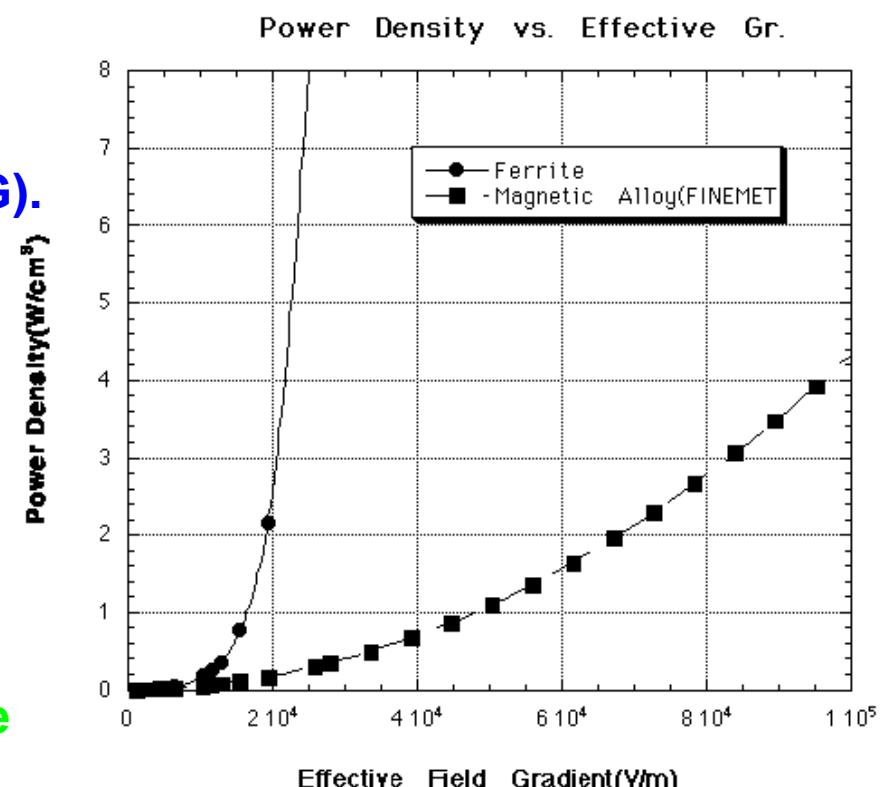
EFG : less than ~15kV/m.

b) Magnetic Alloy

EFG : more than 100kV/m !

MA consumes RF power but not so much for high intensity operation because the beam power is relatively large.

Relative Loading $y = I_b/I_c < 1$



Power Test of High Gradient Test Cavity

TEST CAVITY

*Single core (O.D=580mm,I.D=250mm, t=25mm)

*Direct water cooling

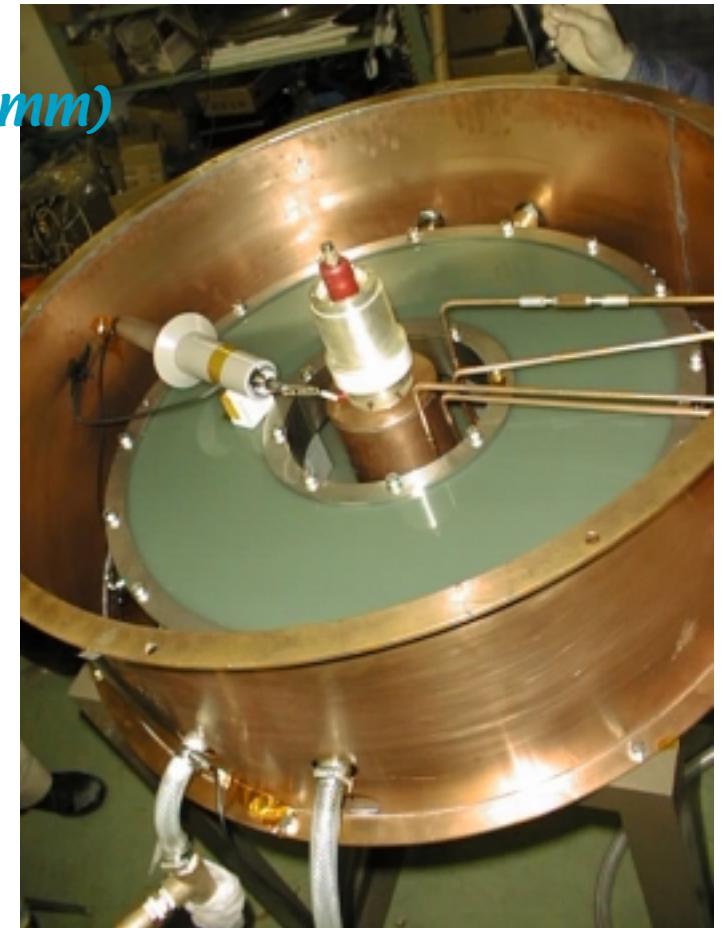
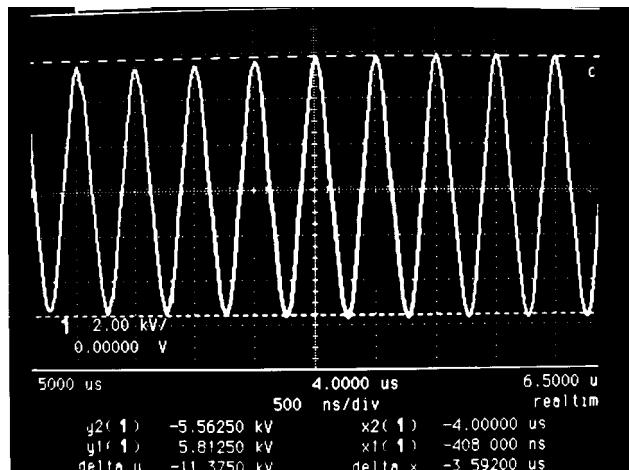
*RF power :30kW max.(B-class)

Achieved:

$EFG = 100\text{kV/m (cw)}$

$EFG = 220\text{kV/m (burst)}$

(limited by RF amplifier)



The gap voltage of the test cavity. The maximum RF voltage of 5.5kV(=220kV/m)was obtained.

Prototype of MA-loaded Cavity

Single Gap MA-loaded Cavity

$E \sim 50\text{kV/m}$

RF Voltage 20kV

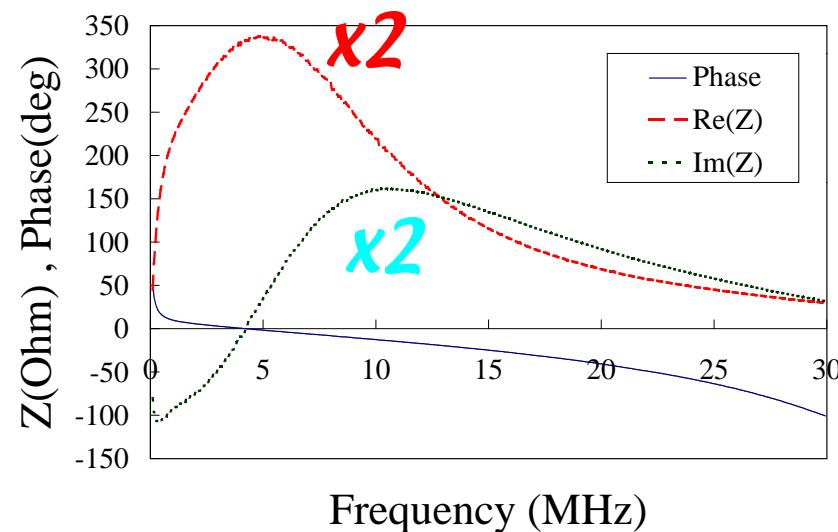
No. of Cores 6

Shunt Impedance 500-750 W

Q 1

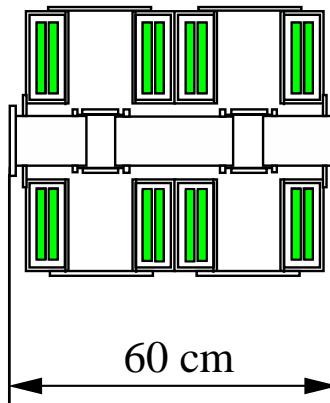
Total Length 40 cm

Measured Cavity Impedance & Phase



MA vs. ferrite

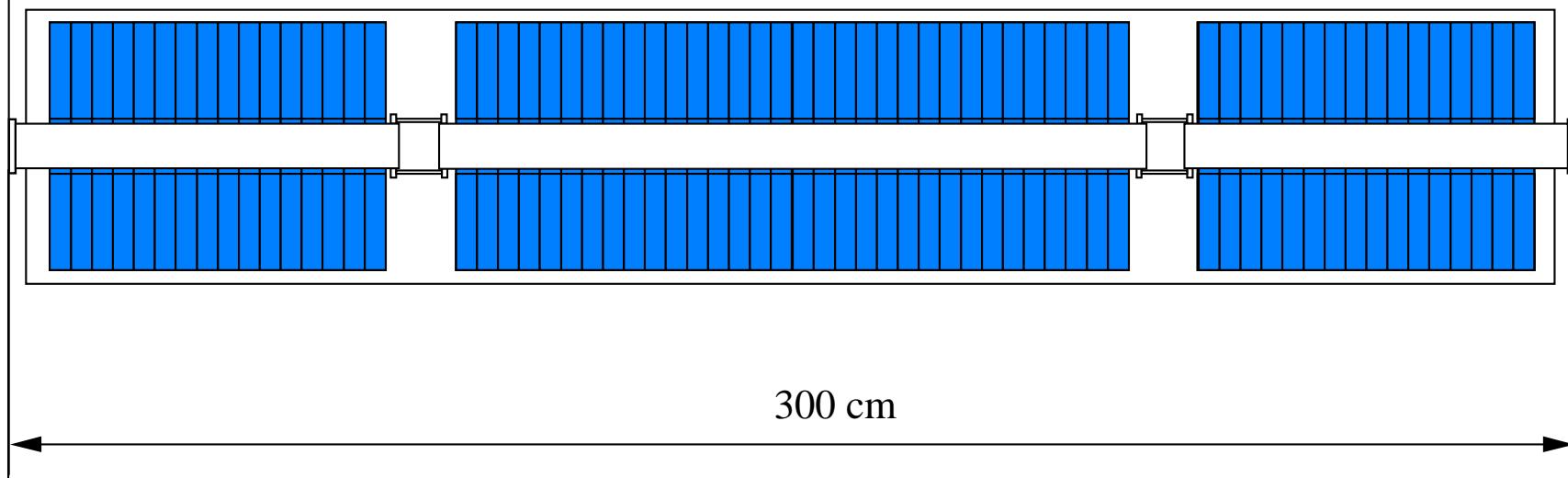
MA-loaded Cavity



RF Voltage
No. of Cores
Total length

	MA	Ferrite
RF Voltage	~40kV	~40kV
No. of Cores	12	68
Total length	0.6m	3m

Ferrite-loaded Cavity



Development of proton FFAG accelerator

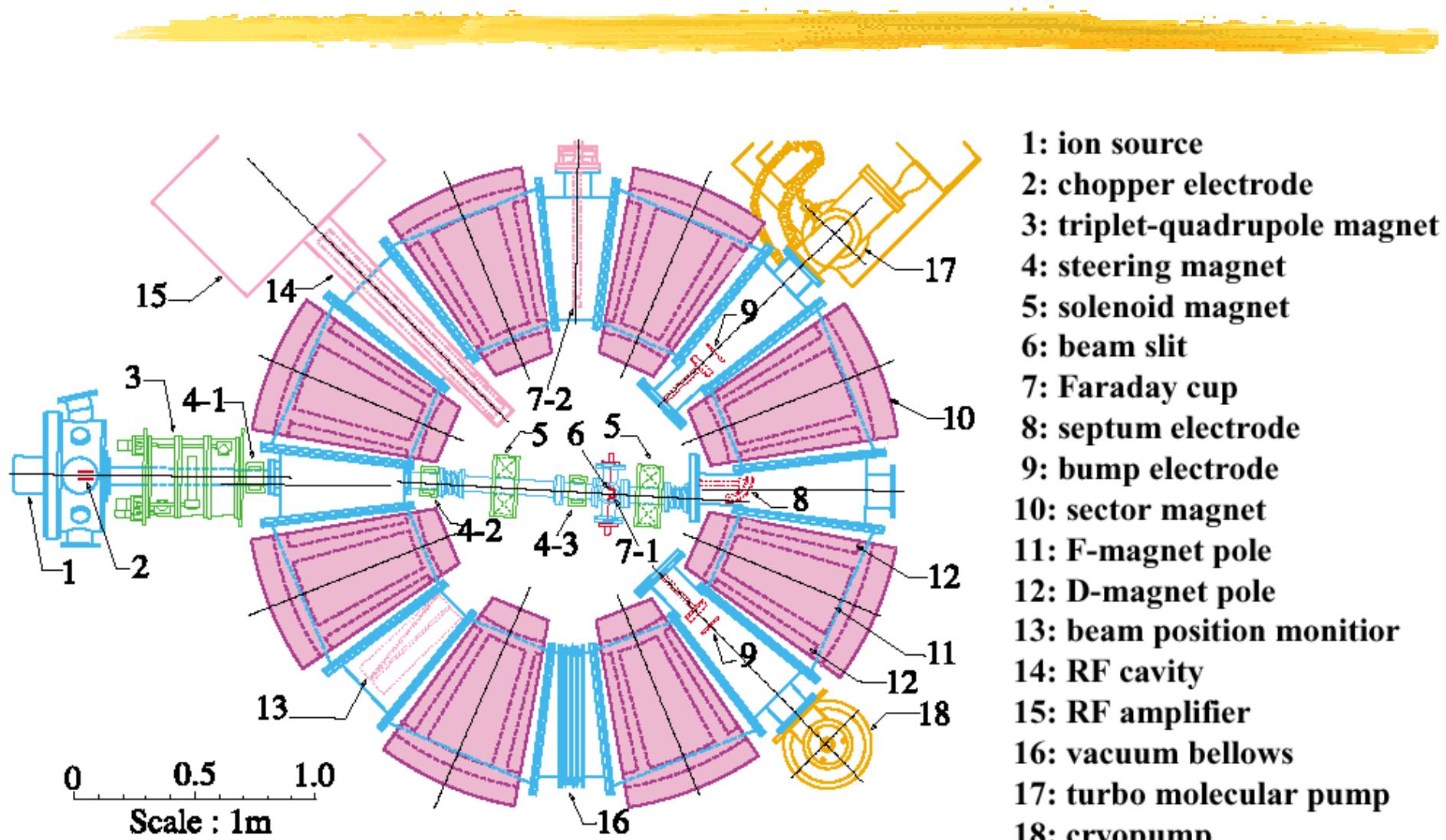
*PoP (proof-of-principle) model using MA cavity
aims:*

- (1) fast acceleration : $t < 1\text{msec} \rightarrow 1\text{kHz rep. rate}$*
- (2) first proton FFAG accelerator*

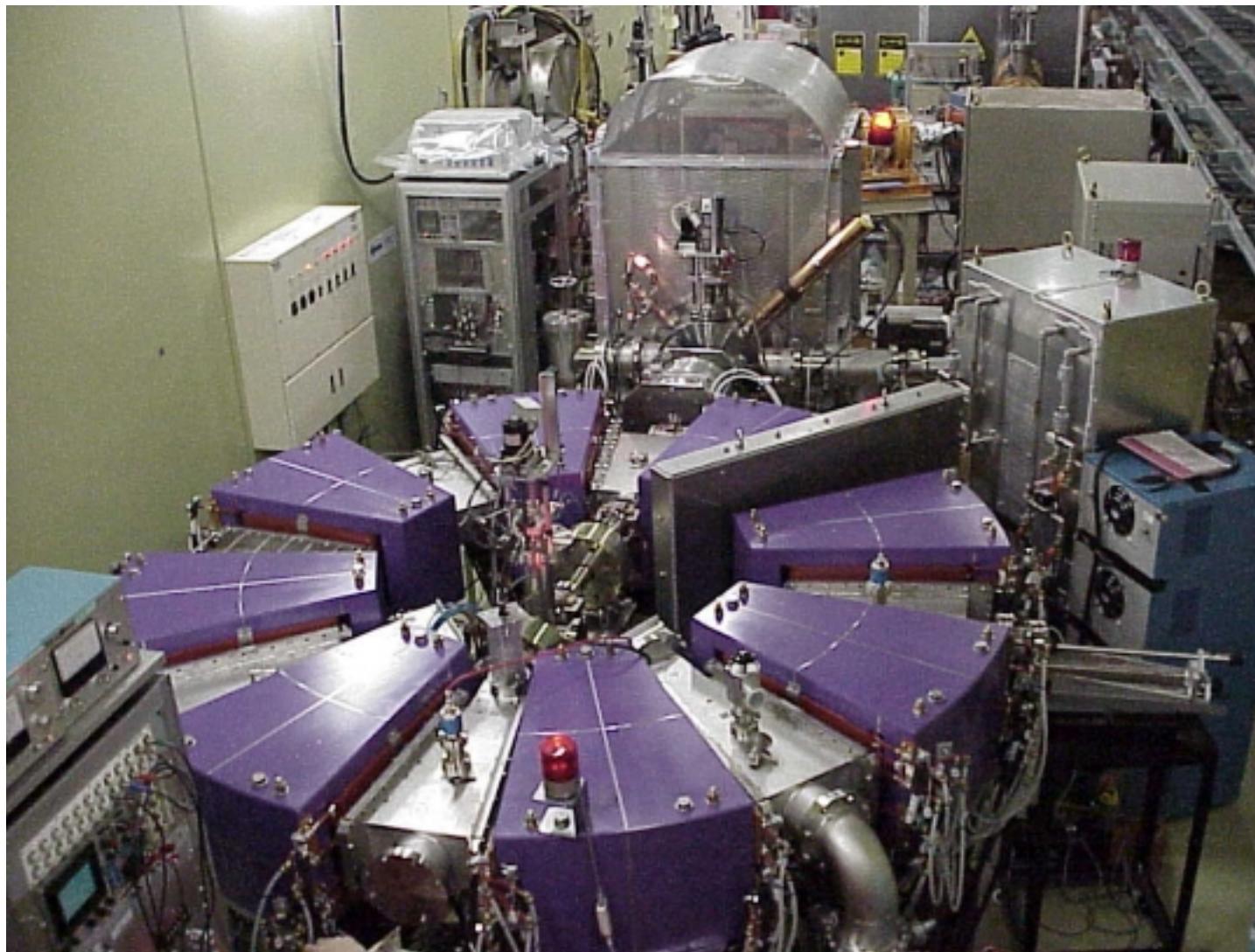
(parameters)

Type of magnet	Radial sector type (Triplet)	
No. of sectors	8	
Field index(k-value)	2.5	
Energy	50keV(injection) ~ 500keV	
Reptition rate	1kHz	
Magnetic field	Focus-mag. :	0.14~0.32Tesla
	Defodus-mag. :	0.04~0.13Tesla
Radial of closed orbit	0.81~1.14m	
Betatron tune	Horizontal :	2.17~2.22
	Vertical :	1.24~1.26
rf frequency	0.61~1.38MHz	
rf voltage	1.3~3.0kVp	

PoP proton FFAG accelerator



PoP proton FFAG model



Radial Sector -Triplet Type

$$\frac{\pi}{N} = \theta_F - \theta_D, N : \text{sector number}$$

geometrical field index : k

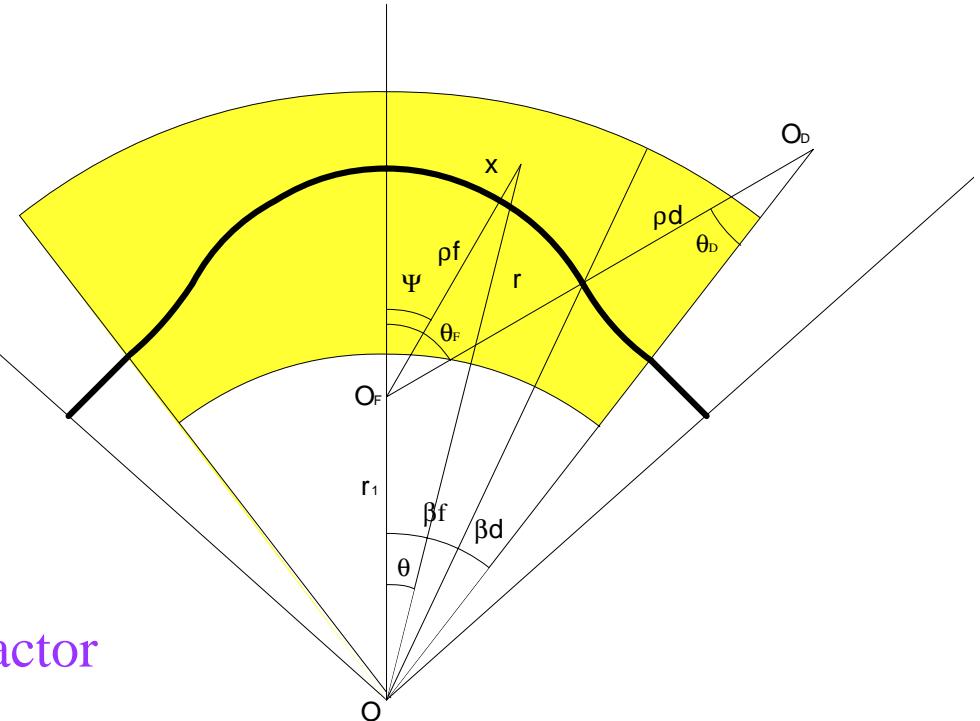
$$\frac{B}{B_0} = \left(\frac{r}{r_0} \right)^k$$

field index (seen by particle): n

$$n = k \frac{1 + \xi \cos \psi}{1 + 2\xi \cos \psi + \xi^2}$$

$$\xi = \zeta - 1, \quad \zeta = \frac{r_0}{\rho_{F,D}} : \text{circumference factor}$$

$$\alpha = \frac{1}{k+1} : \text{momentum compaction factor}$$

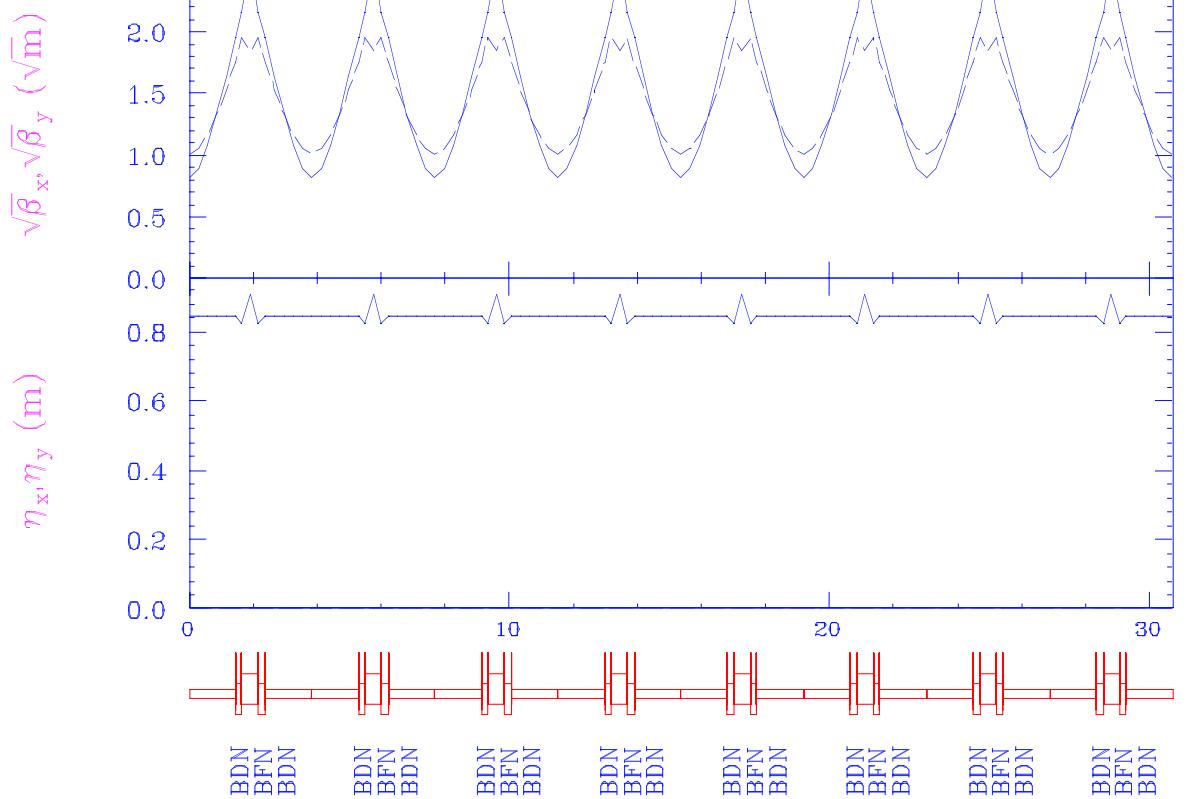


Beam Optics Parameters

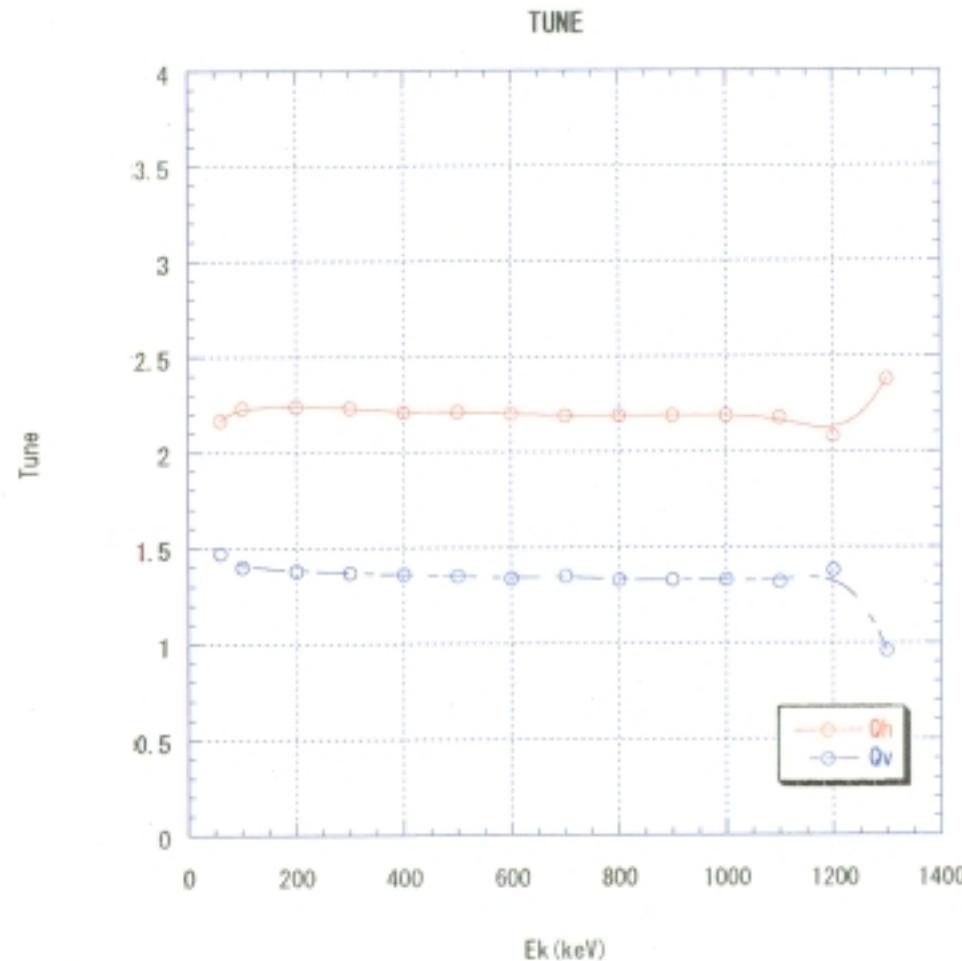
Linearized beam parameters : SAD

betatron tunes

ν_x	3.13
ν_y	2.78



Betatron tunes vs. beam energy

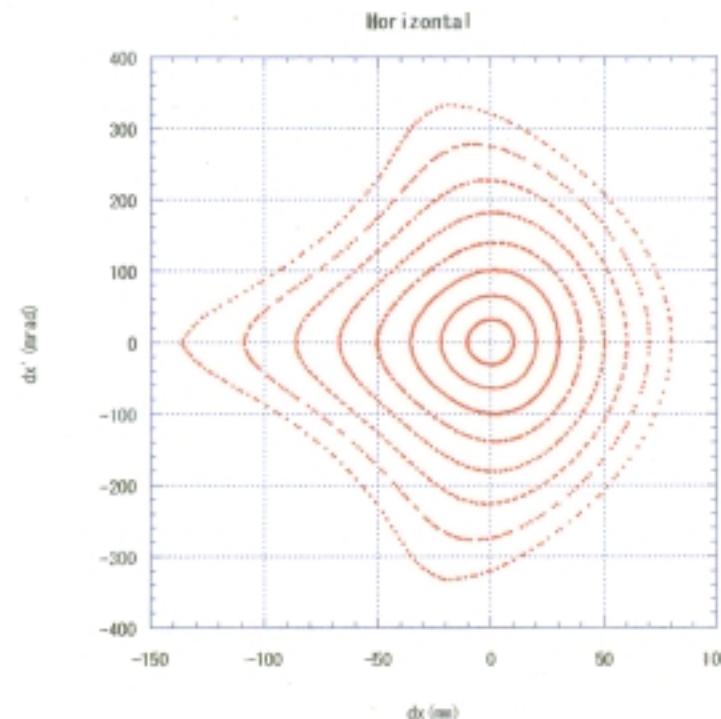


Acceptance

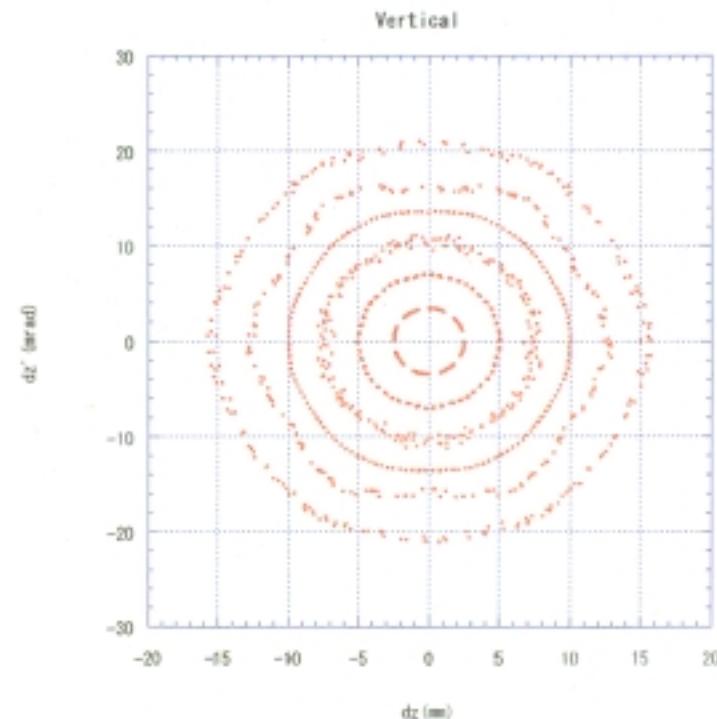
@500keV
200Turns

$$A_h > 10000 \text{ mm.mrad}$$
$$A_v > 300 \text{ mm.mrad}$$

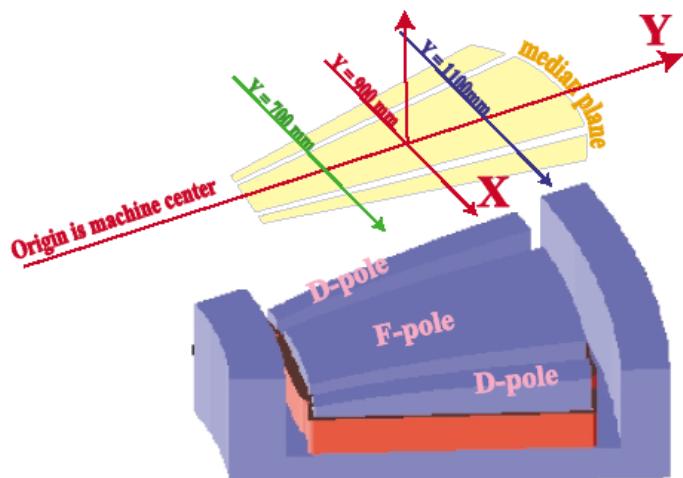
Horizontal(Wv=0pimmmrad)



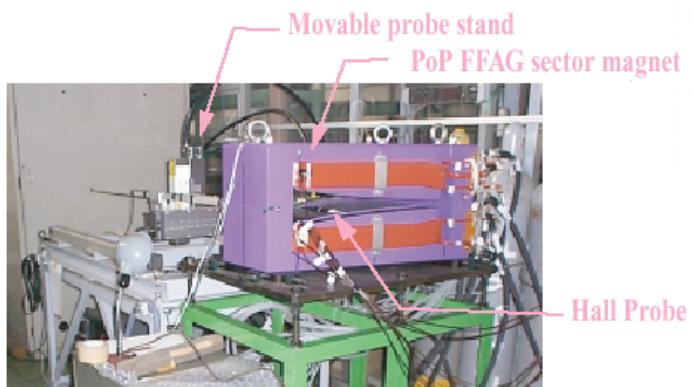
Vertical(Wh=0pimmmrad)



Magnetic field configuration

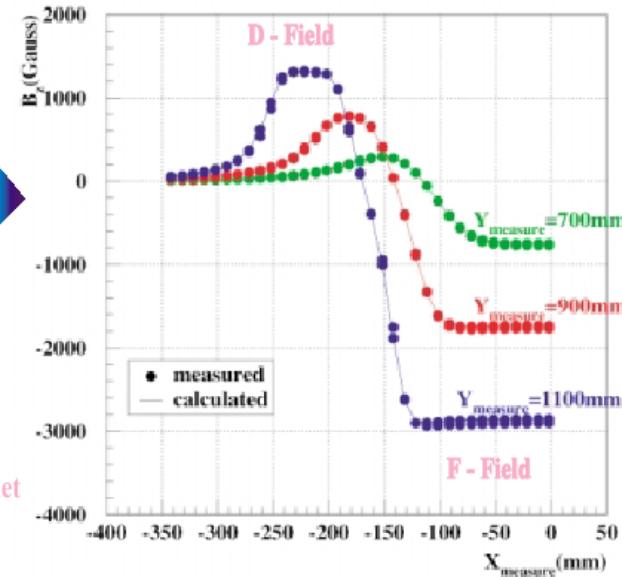


((A schematic view of the PoP FFAG sector magnet))

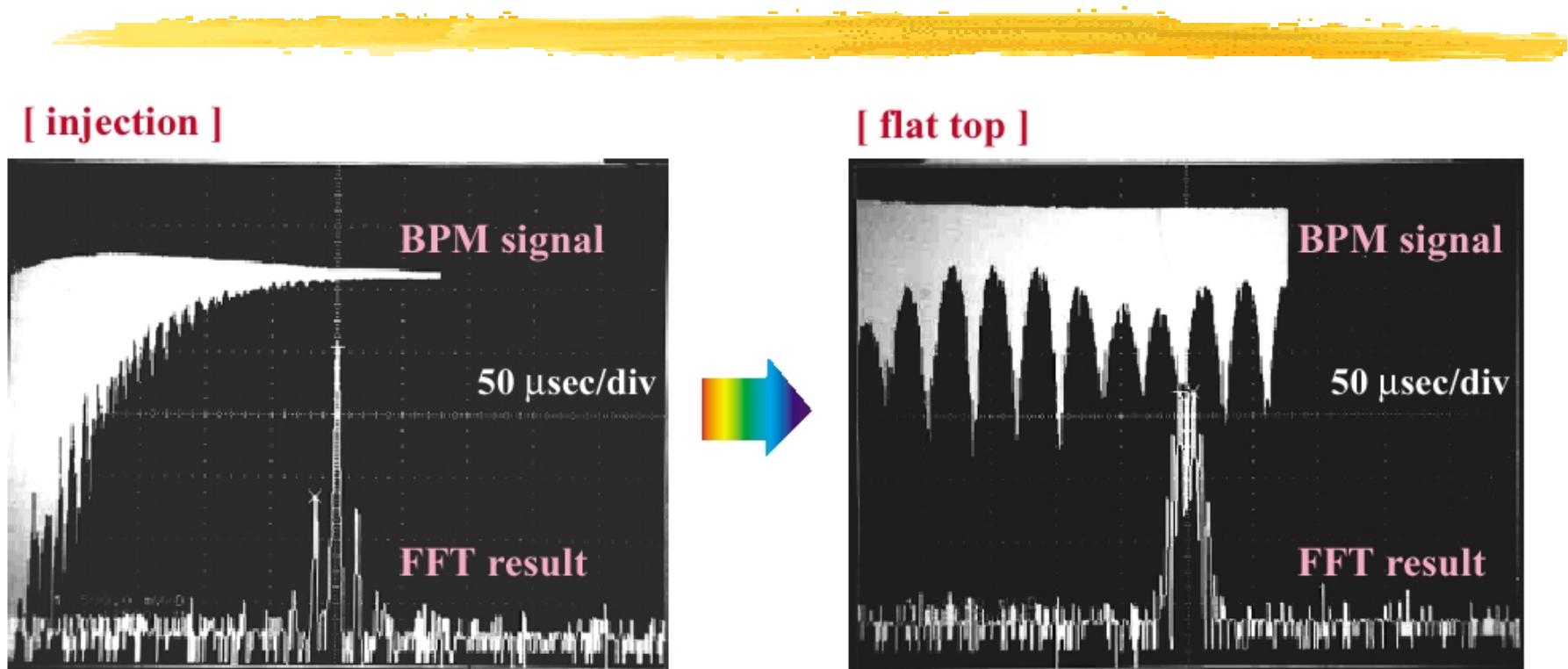


((The setup of the sector magnet measurement))

[Measured magnetic field, and calculated field by TOSCA]



Beam Acceleration



revolution frequency :

610kHz

→ 1.251MHz

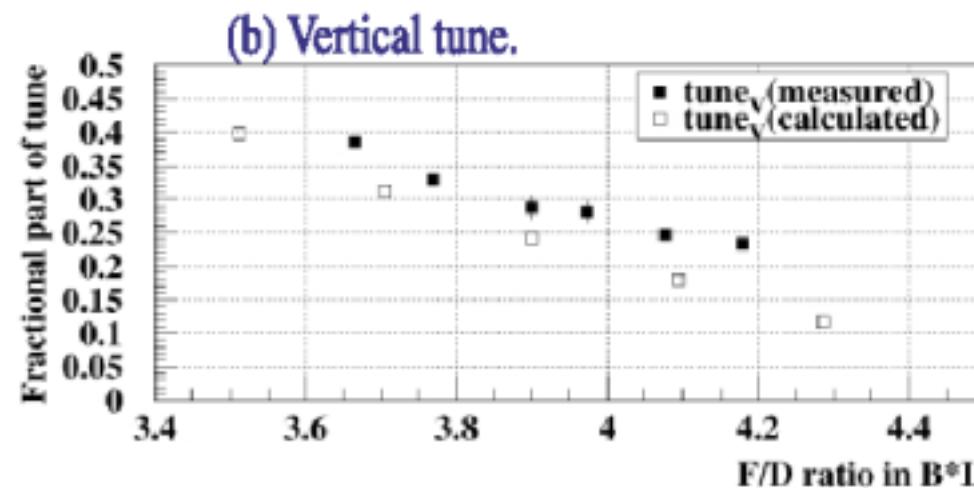
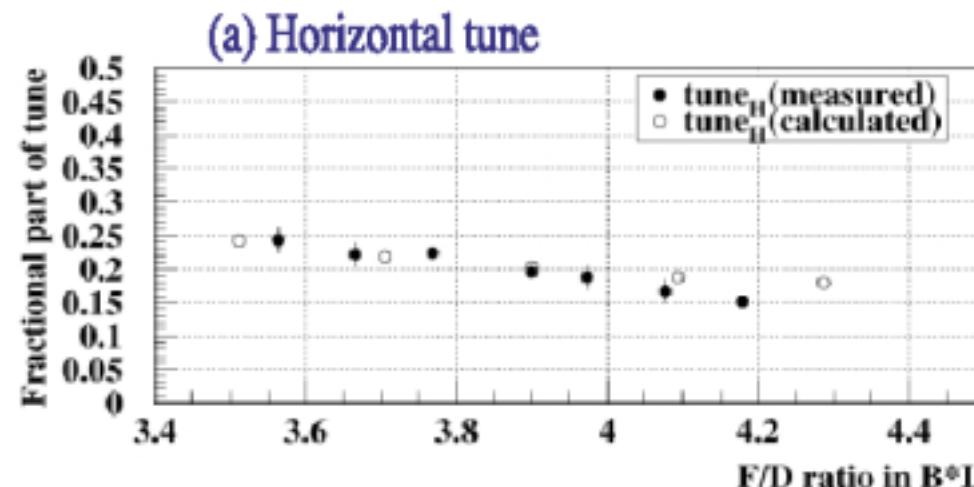
synchrotron frequency :

24.06kHz

→ 16.78MHz

Measured Betatron Tunes

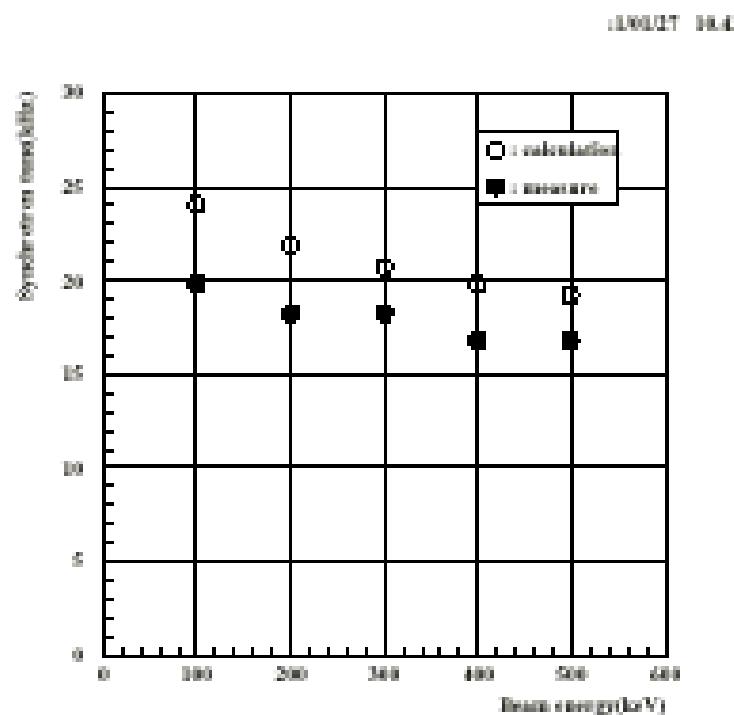
[Betatron tune in various magnetic field]



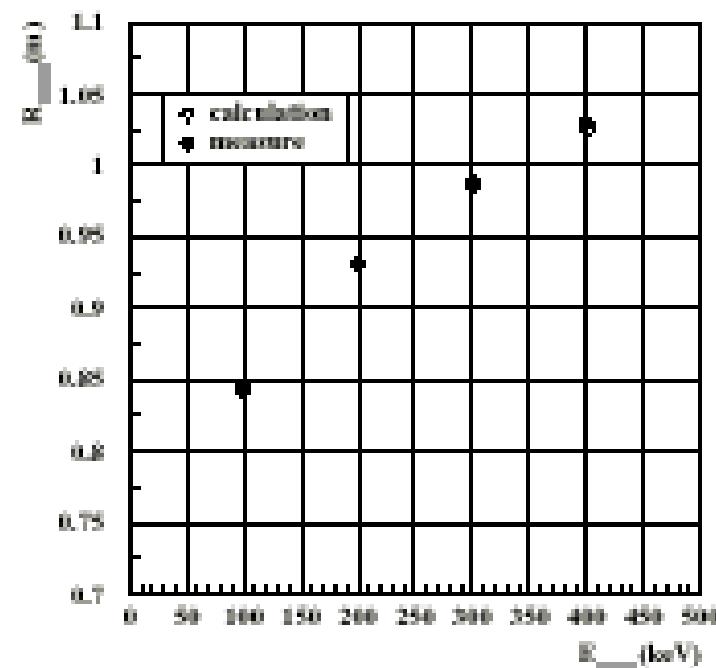
Measured Beam Parameters

beam parameters vs energy

f_s vs Energy



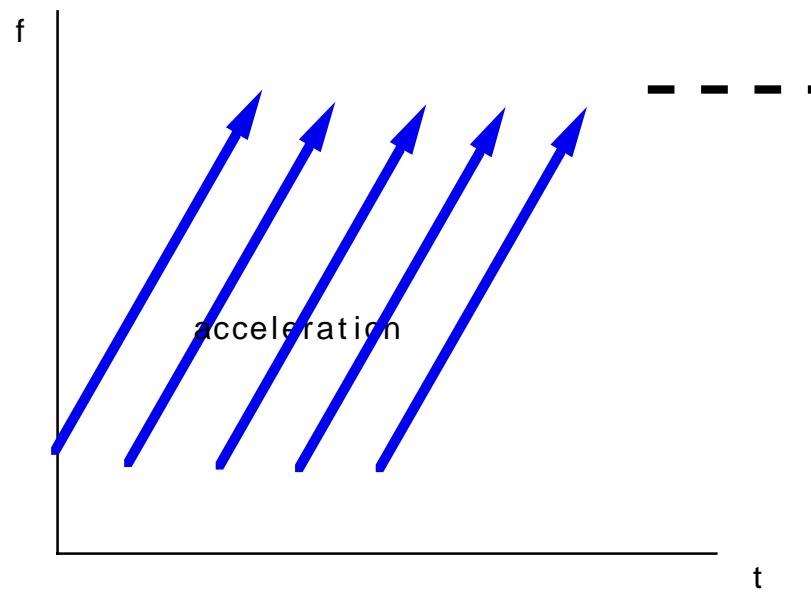
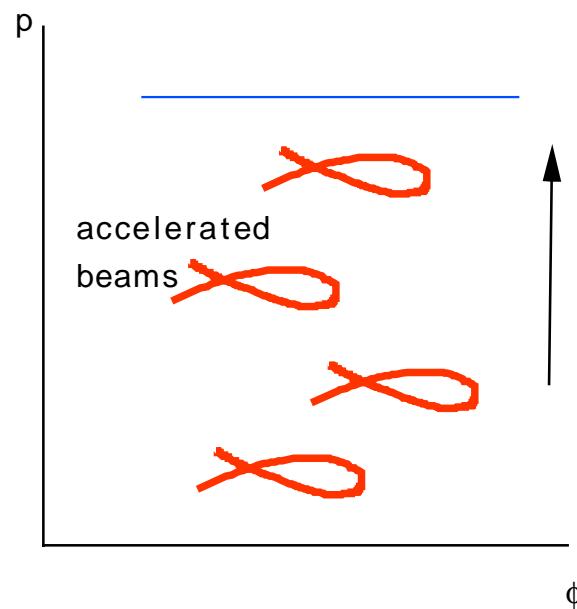
Radial position vs Energy



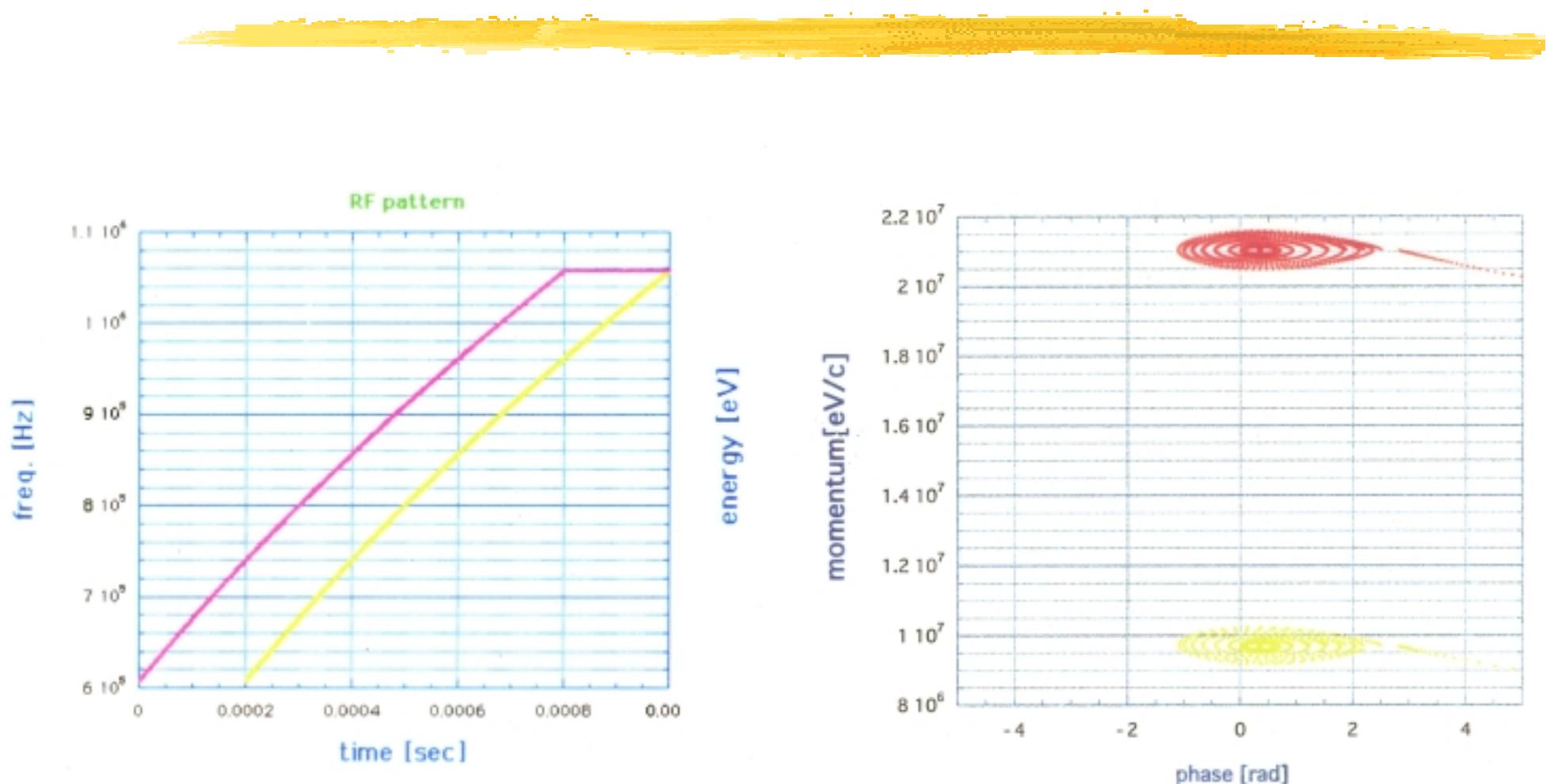
Multi-bunch Acceleration



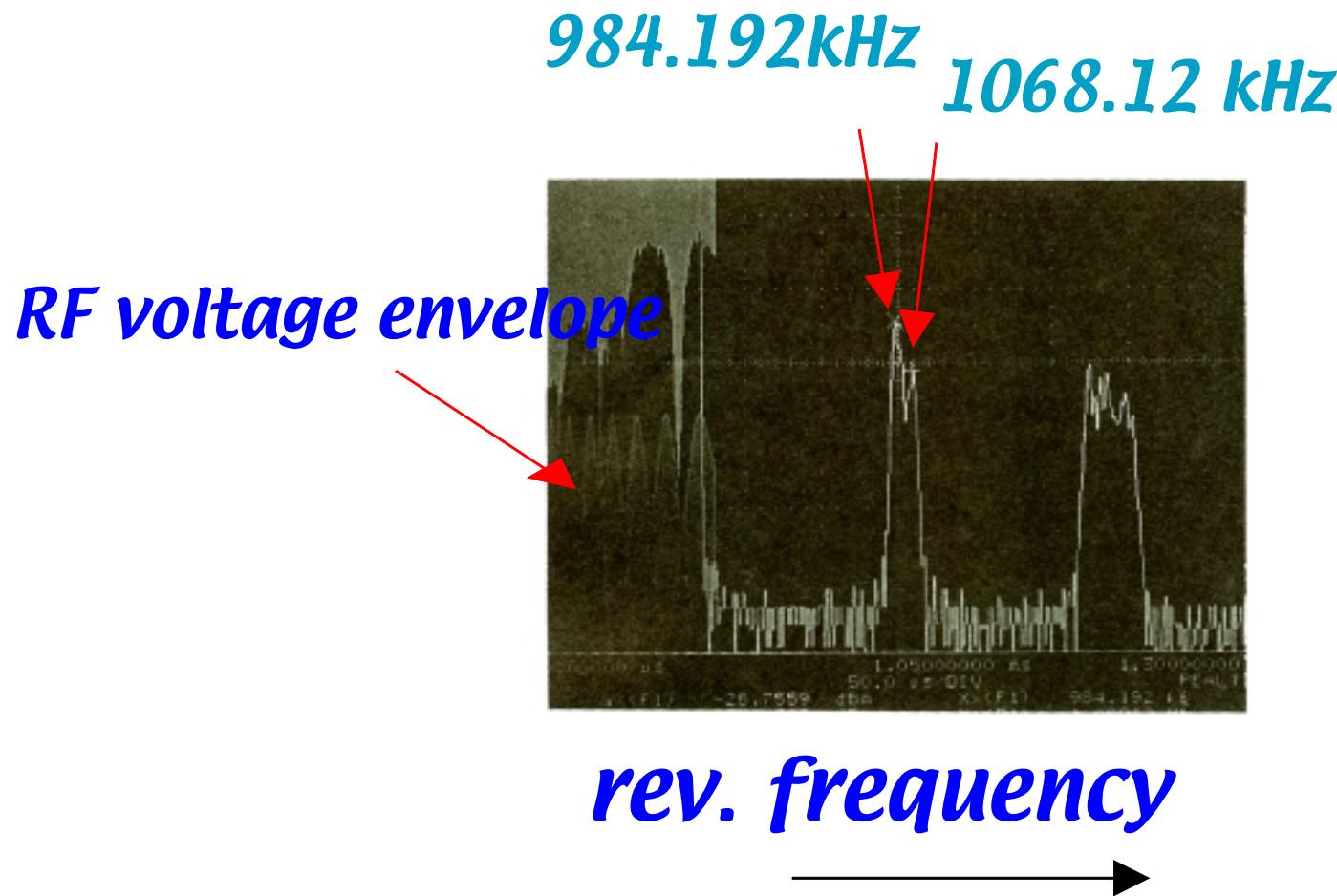
Higher Repetition Rate : $\times m$ 1kHz \rightarrow 10kHz ($m=10$)



Two bunch acceleration in PoP FFAG



Two beam acceleration - Experiment



150-MeV proton FFAG accelerator

Prototype for various applications:

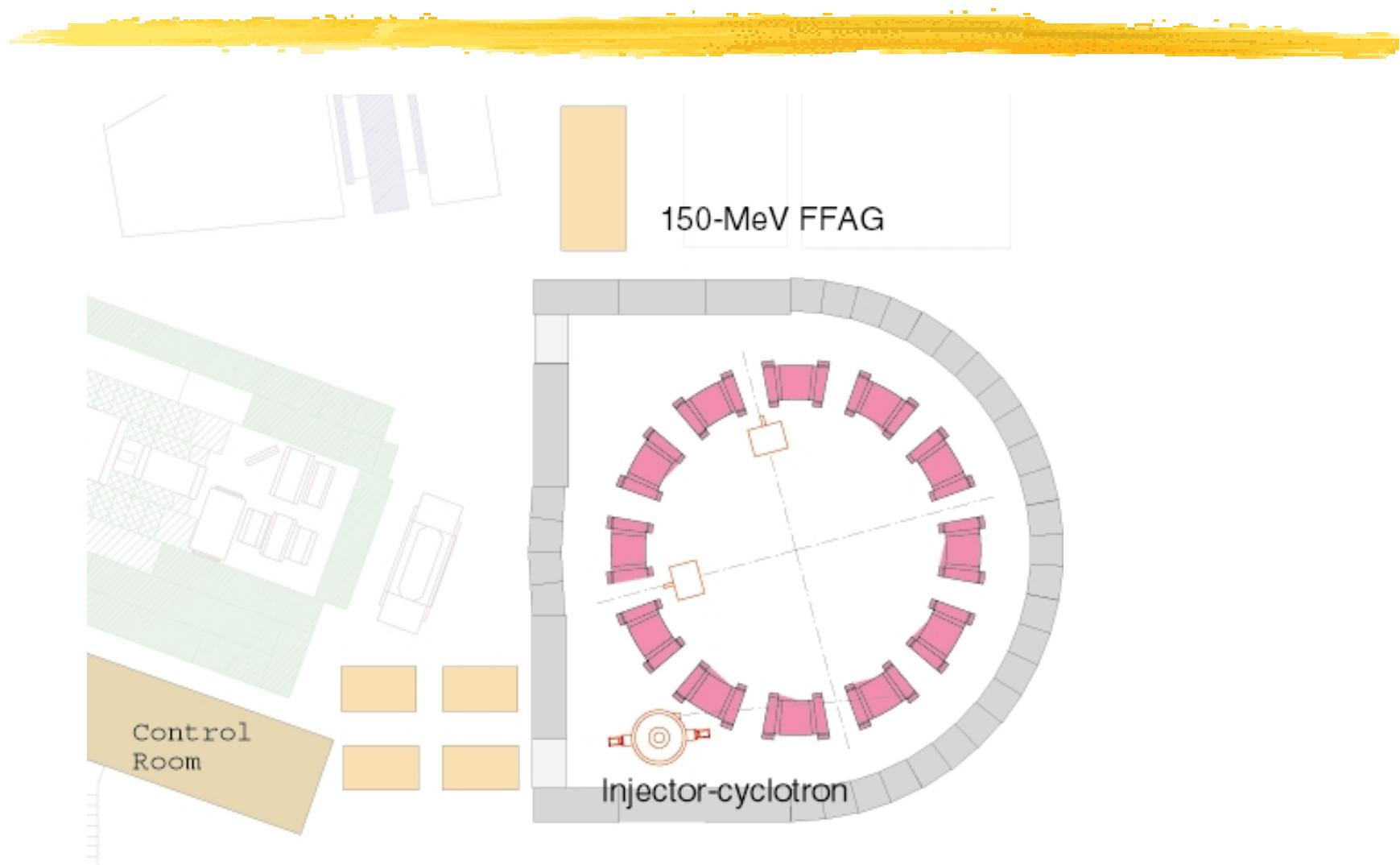
Radical application : Cancer therapy

Muon phase rotation : PRISM project

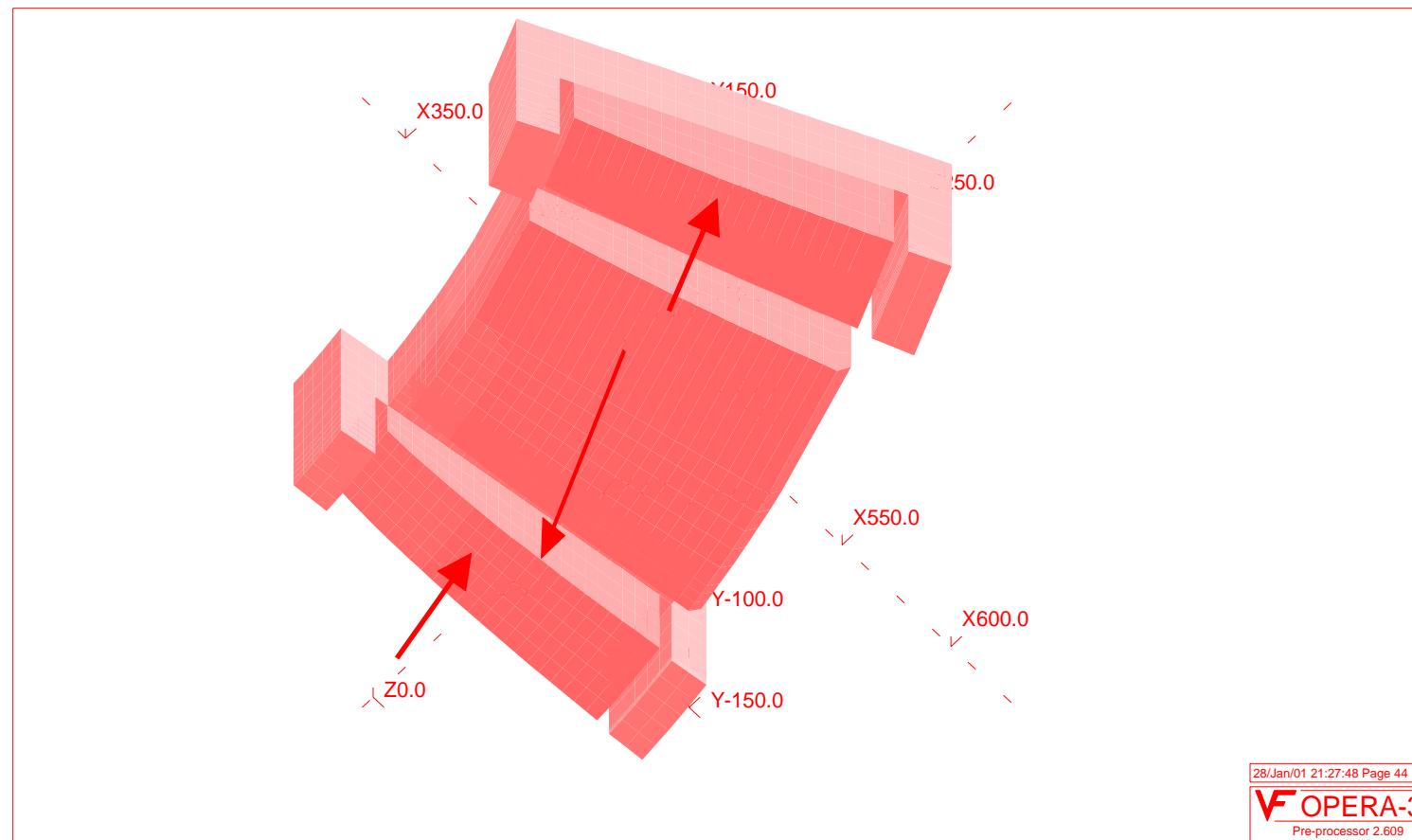
150MeV FFAG main parameters

No. of sectors	12
Field index(k -value)	7.5
Energy	12MeV - 150MeV
Repetition rate	250Hz
Max. Magnetic field	
Focus-mag.:	1.63 Tesla
Defocus-mag.:	0.13 Tesla
Closed orbit radius	4.4m -5.3m
Betatron tune	
Horizontal :	3.8
Vertical :	2.2
rf frequency	1.5 -4.6MHz

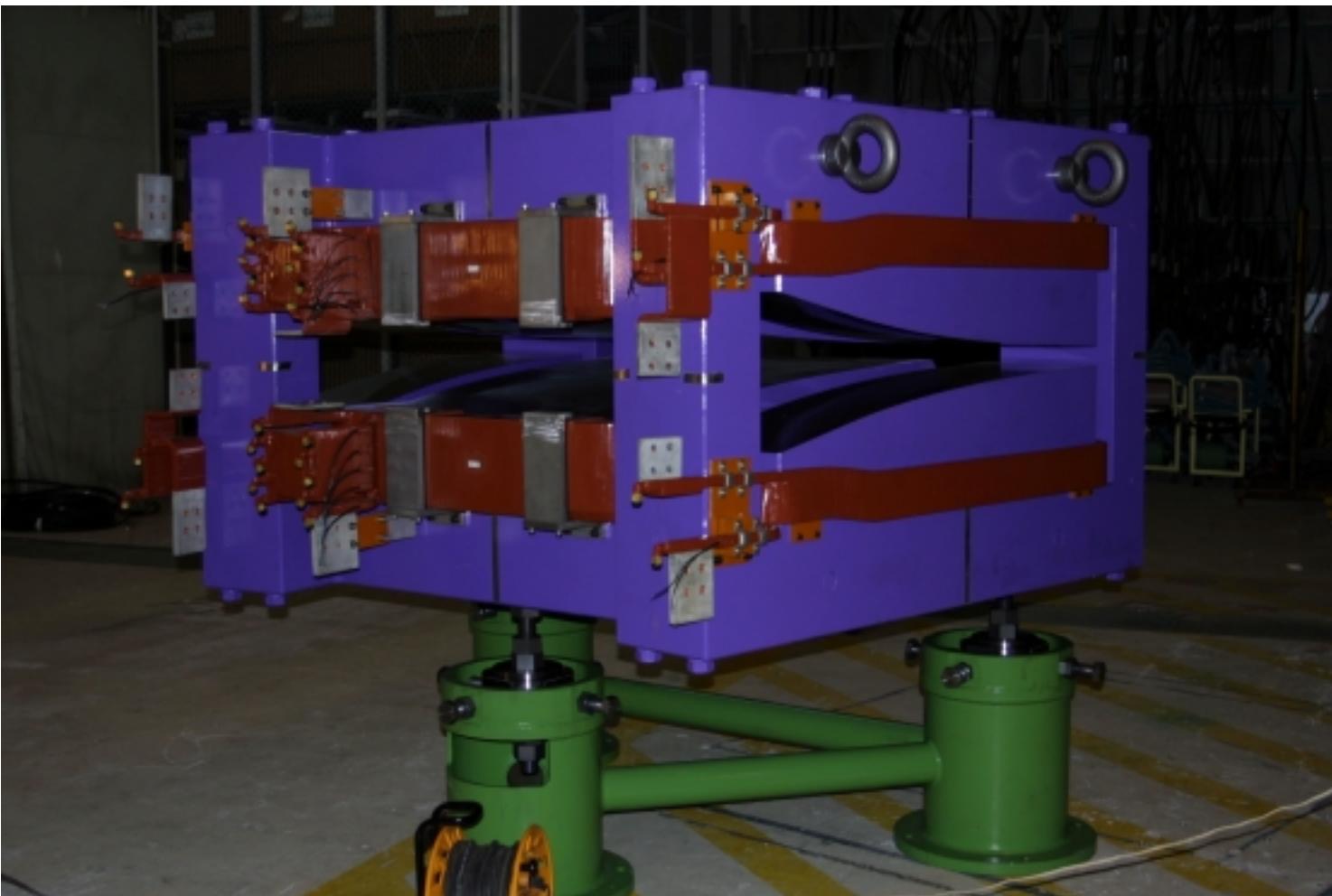
150-MeV proton FFAG accelerator



Yoke-free magnet of triplet sector FFAG



Magnet of 150-MeV proton FFAG



Neutrino Factory

*High Intensity & High Energy Neutrino Beam
muon acceleration : 20-50 GeV*

+
muon storage : -
Conventional Scheme $\mu \rightarrow \bar{v}_e$
---> “ PJK “ Scenario
based on linear accelerator

Introduction



Why Neutrino Factory in Japan?

1 Neutrino Physics in Japan

Super-KAIMIOKANDE(atmospheric neutrino)

Long Base-line (KEK 12-GeV PS to KAMIOKA) K2K

2 High Intensity Proton Accelerator Project

Proton Driver beam power > 1 MW

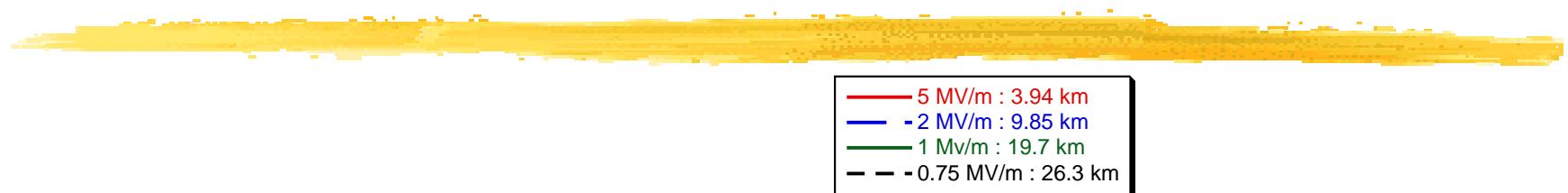
50-GeV PS Joint Project KEK/JAERI

Muon Survival for various accelerating fields

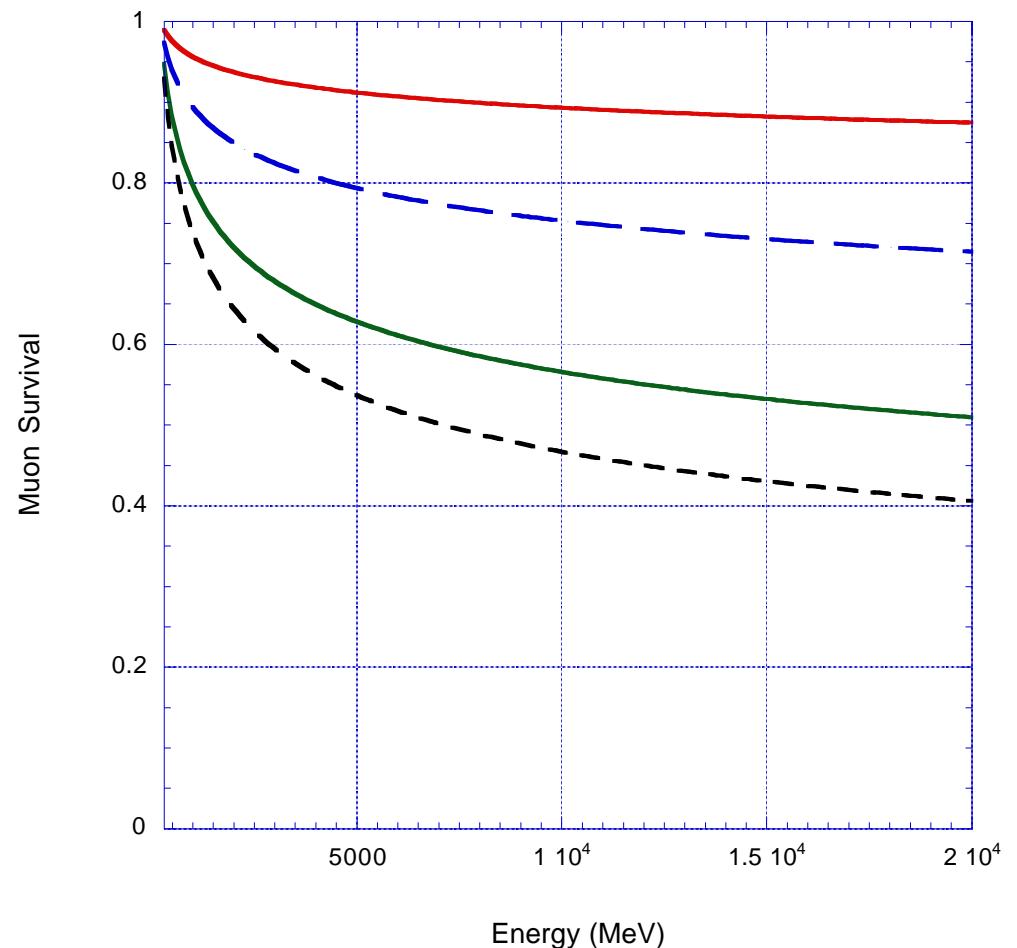
0.3 GeV/c - 20 GeV/c

$E=5\text{MV/m} \rightarrow 3.9\text{ km}$

$E=0.75\text{MV/m} \rightarrow 26.3\text{ km}$



- 5 MV/m : 3.94 km
- - 2 MV/m : 9.85 km
- 1 MV/m : 19.7 km
- - 0.75 MV/m : 26.3 km



Neutrino Factory Scenario

Linear Accelerator Scenario (PJK Scenario)

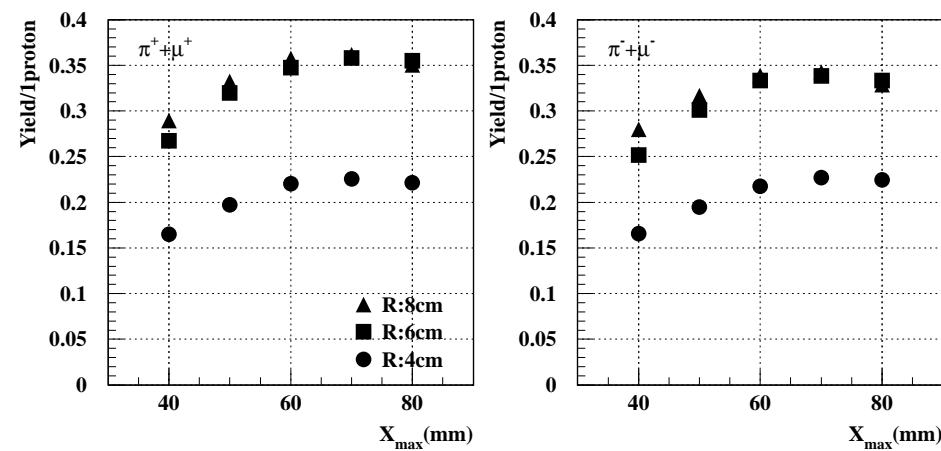
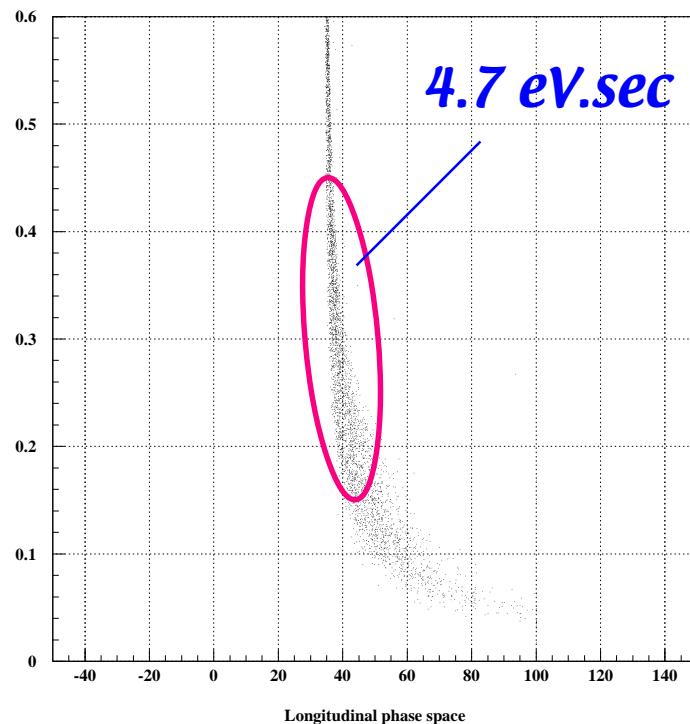
- *accelerating field Gradient : $E > 5 \text{ MV/m}$ ($L \sim 4 \text{ km}$)
- > 1) *high frequency rf* ($f > 100 \text{ MHz}$)
 - 2) *phase rotation & Muon cooling*
large emittance ($\varepsilon_{H,V}$ & $d\mathbf{p}/\mathbf{p}$)

Ring Accelerator Scenario (FFAG Scenario)

- > 1) *# of turns* $\sim >30$ turns ($R \sim 0.15 \text{ km}$)
- 2) *low frequency rf* ($f \sim 5-10 \text{ MHz}$)
- 3) *no phase rotation & no cooling*

Accelerator Scenario - FFAG Option

*Direct Acceleration by Low Frequency RF
No Phase Rotation, No Cooling*



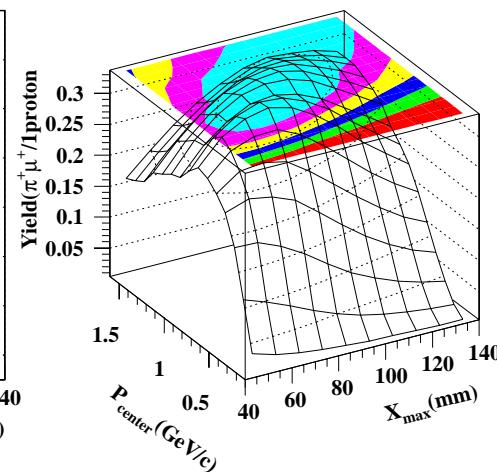
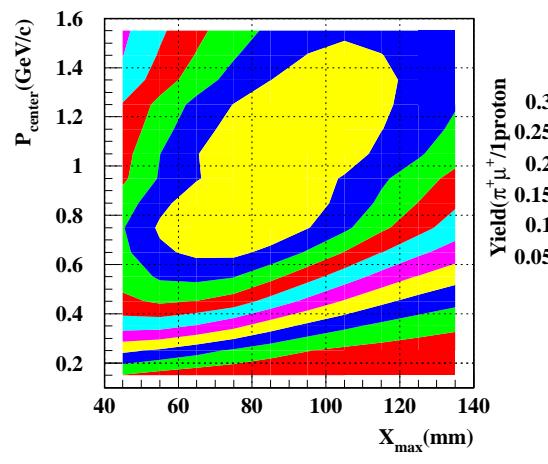
$\Delta p/p = \pm 50\% @ 300\text{MeV}/c, A = 0.01 - 0.02\pi\text{m.rad}$

~ 0.3 muons / proton @ 50-GeV PS

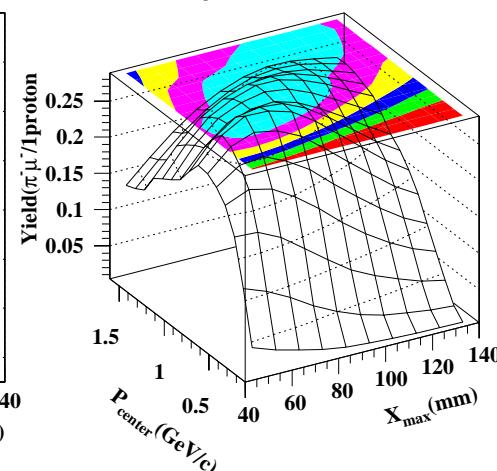
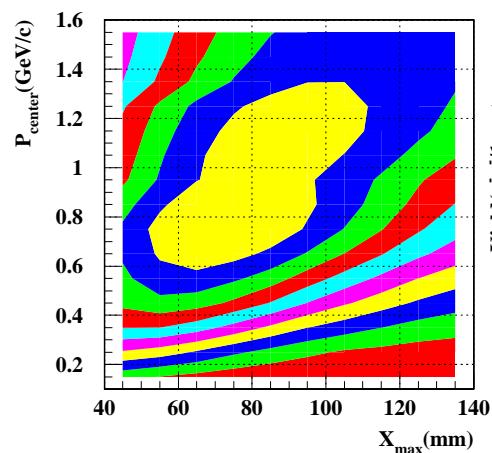
Muon & Pion yield with fixed trans. acceptance

$$\varepsilon_n(100\%) = 30,000 \text{ mm.mrad}$$

$$dp/p = \pm 50\%$$



$\pi^+ - \mu^+$



$\pi^- - \mu^-$

Accelerator Scenario - FFAG Option

FFAG(Fixed-Field Alternating Gradient) Accelerator

(1) Large Momentum Acceptance

$\Delta p/p \sim \pm 50\% \text{ or more}$

(2) Large Aperture

$A \sim 0.01-0.02 \pi m.\text{rad}$

(3) Scaling

$p/p_0 \sim (r/r_0)^{k+1}$: tunes=const., $\xi=0$, $\alpha=1/(k+1)$: no

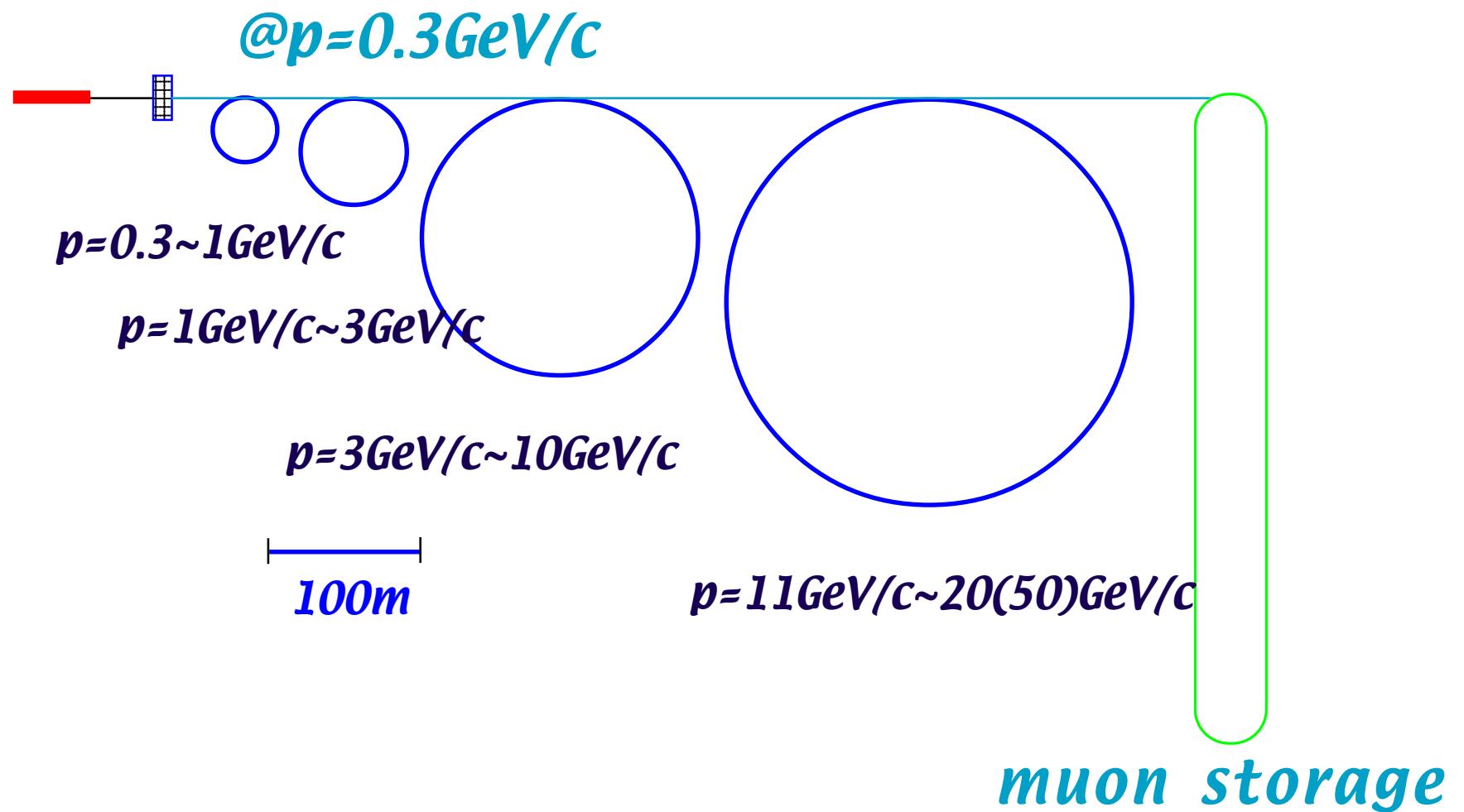
higher orders

(4) Non-scaling

linear system

Accelerator Scenario - FFAG Option

- (1) Low Freq. (\sim MHz) & High Gradient RF $E > 1\text{MV/m}$
(2) Acceptance : Trans.: $0.01\text{-}0.02\pi\text{m.rad}$, Long. $\Delta P/P \sim \pm 50\%$



Parameters

Conventional

based on PJK scheme

proton driver *50GeV(1-4MW)*

phase rotation *80MeV/c*

cooling *100m*

acceleration

linac *2GeV*

FFAG *2-11GeV*

RCL *11-20(50)GeV*

storage ring *C~1000m*

Intensity

phase 1 *10^{20} muon/y (1MW)*

phase 2 *4×10^{20} muon/y (4MW)*

New Scheme

no phase rotation,no cooling

proton driver *50GeV(1-4MW)*

Accelerator

FFAG-0(PRISM) *0.3-1GeV*

FFAG-1 *1-3 GeV*

FFAG-2 *3-10 GeV*

FFAG-3 *10-20 GeV*

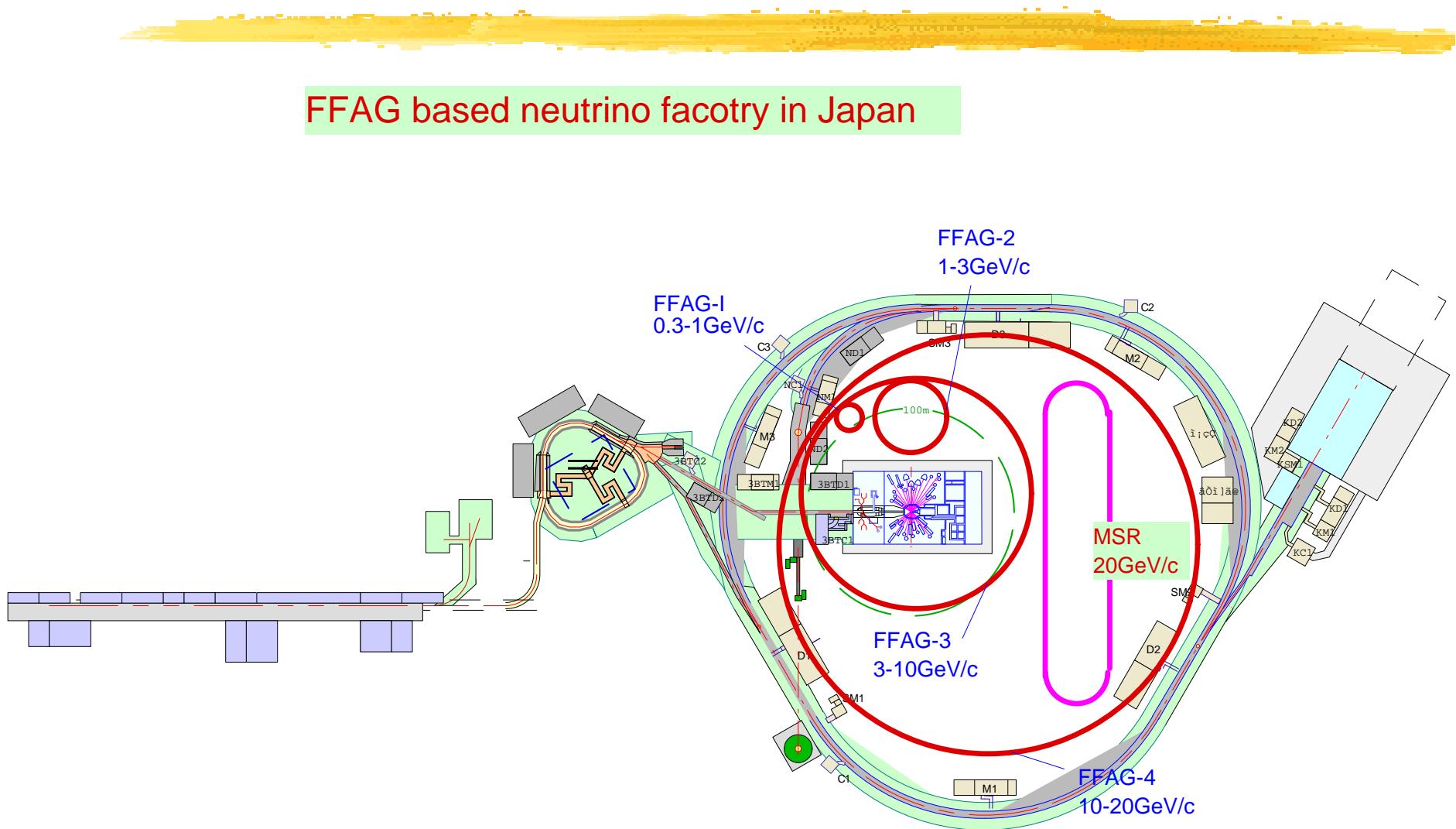
storage ring *C~800m*

Intensity

phase 1 *3×10^{20} muon/y(1MW)*

phase 2 *1.2×10^{21} muon/y(4MW)*

Neutrino Factory in Japan - FFAG Scenario

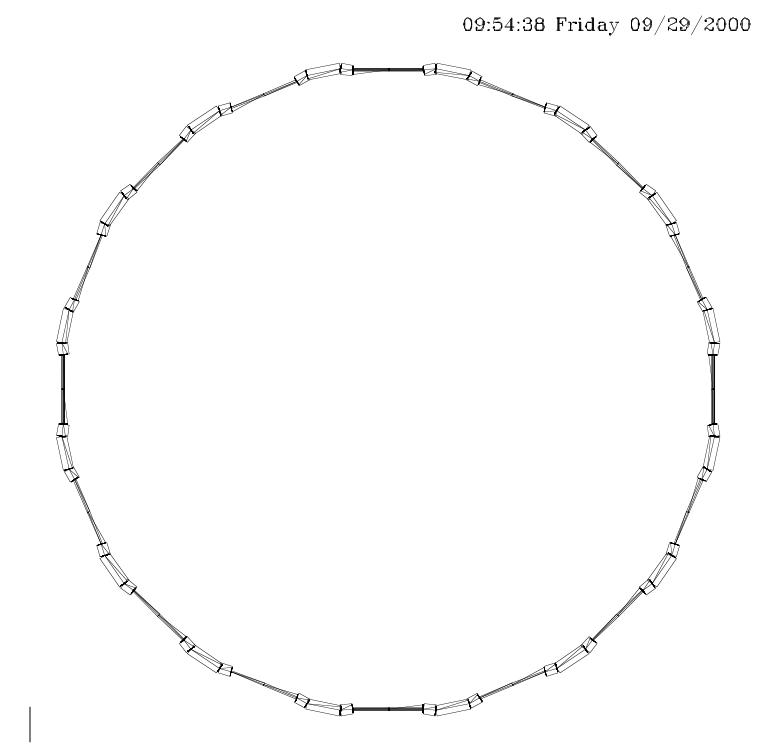
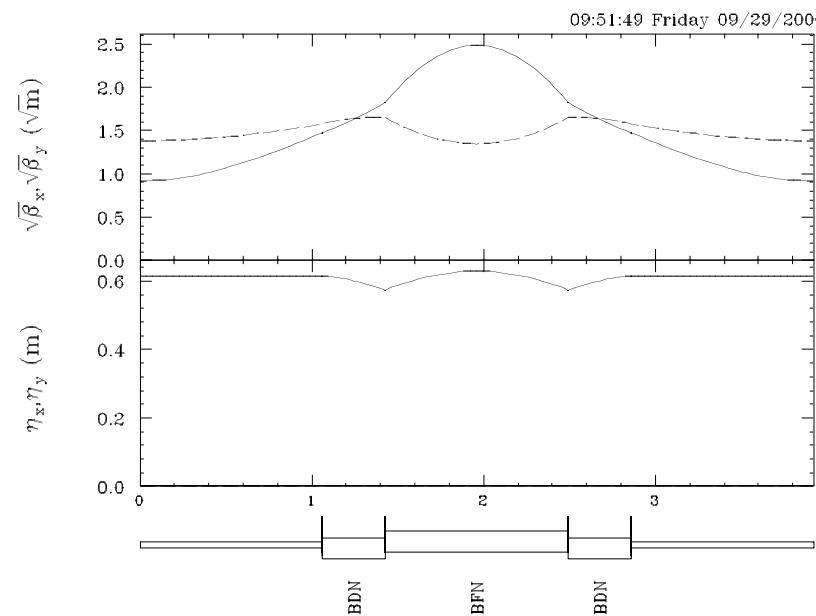


FFAG Parameters

	0.3~1	1~3	3~10	10~20
<i>momentum(GeV/c)</i>	0.3~1	1~3	3~10	10~20
<i>number of sector</i>	16	32	64	120
<i>k number</i>	15	63	220	280
<i>average radius(m)</i>	10	30	90	200
<i>max. B field(T)</i>	2.8	3.6	5.4	6.0
<i>tune</i>	5.826	13.704	27.911	22.333
	4.590	4.048	4.089	6.333
<i>drift length(m)</i>	2.120	3.299	5.046	5.668
<i>BF length(m)</i>	1.065	1.575	2.169	2.685
<i>BD length(m)</i>	0.367	0.544	0.813	1.062
<i>orbit excursion(m)</i>	0.77	0.52	0.813	0.49
<i>transition γ</i>	4	8	14.9	16.8

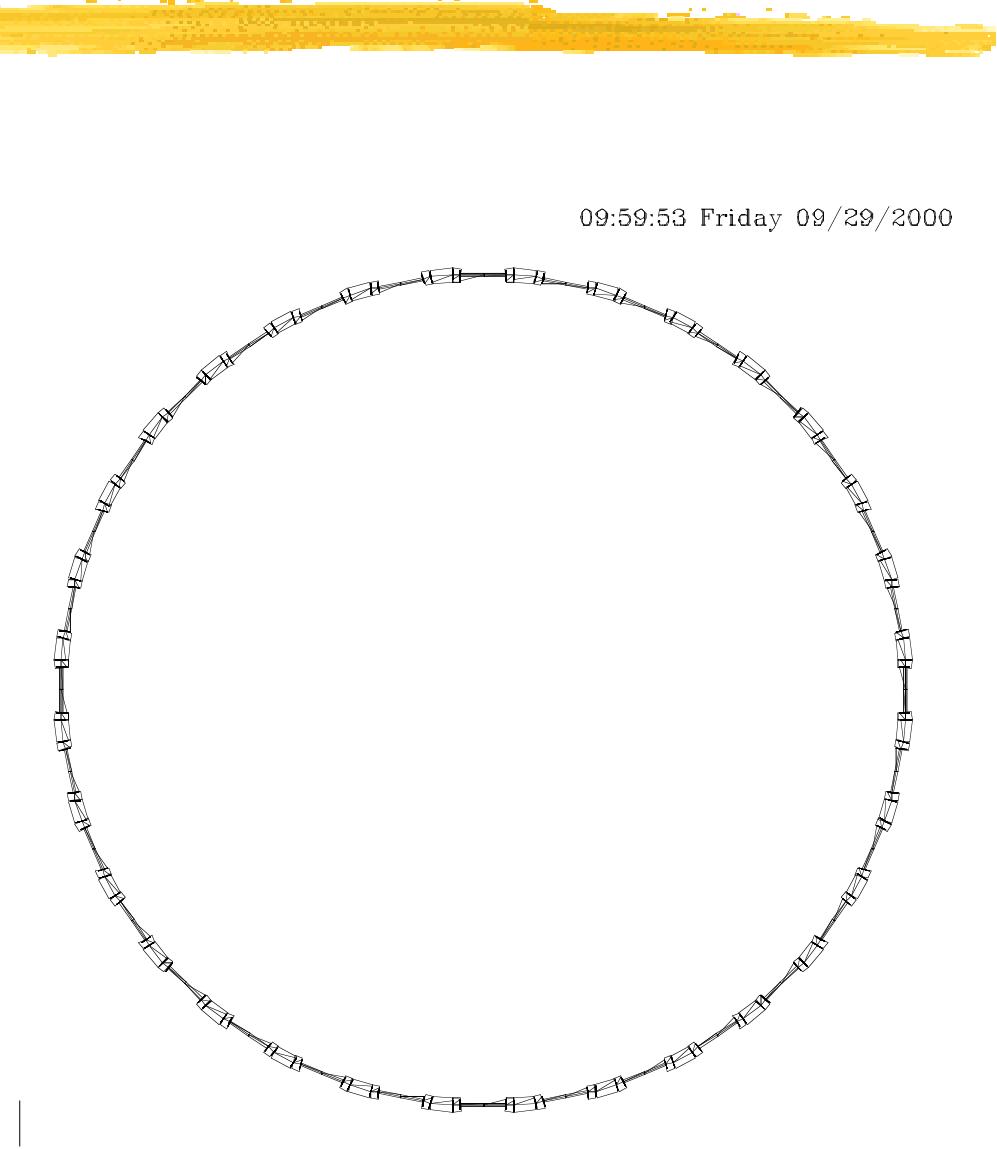
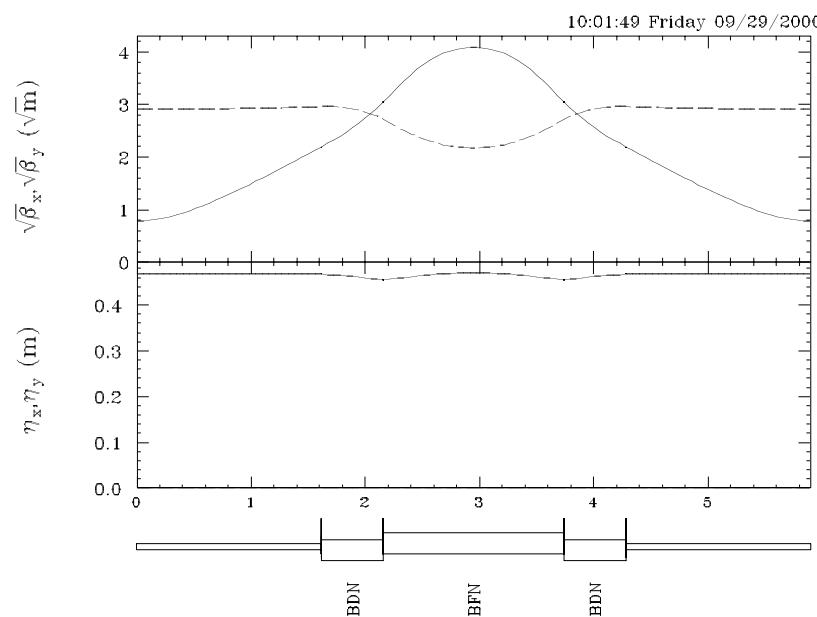
FFAG 0.3 - 1 GeV

r 10m
of sector 16
B field 2.8T



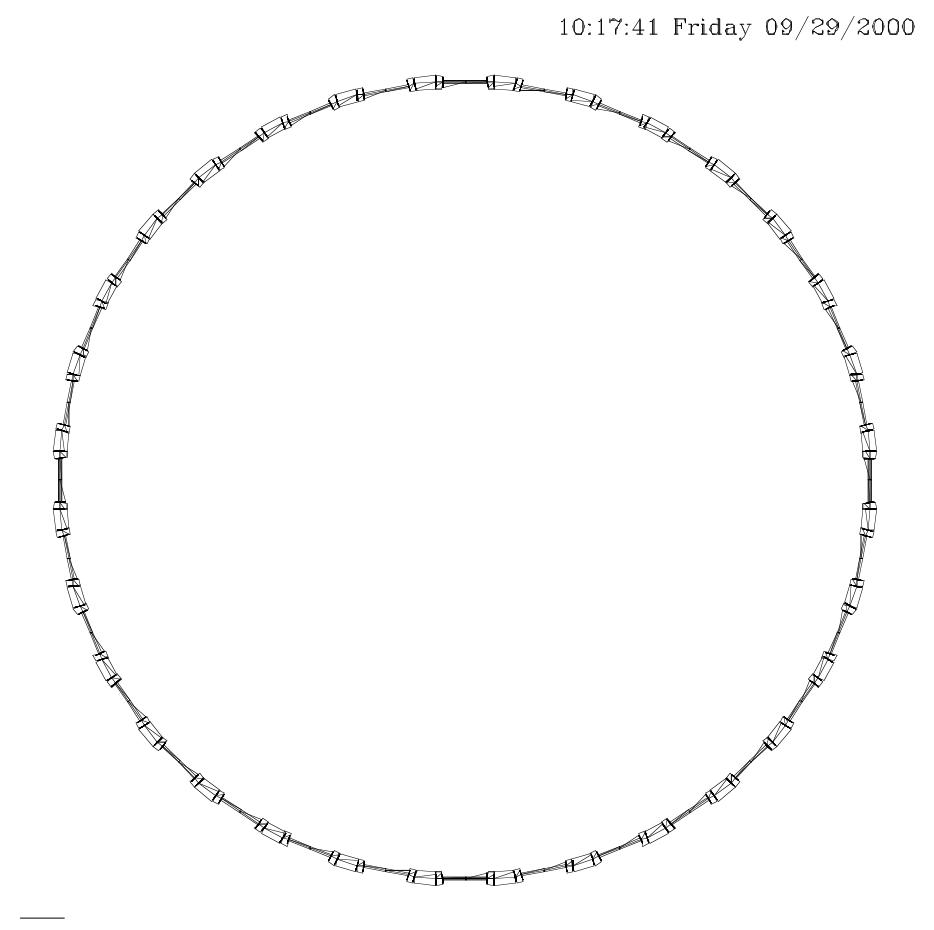
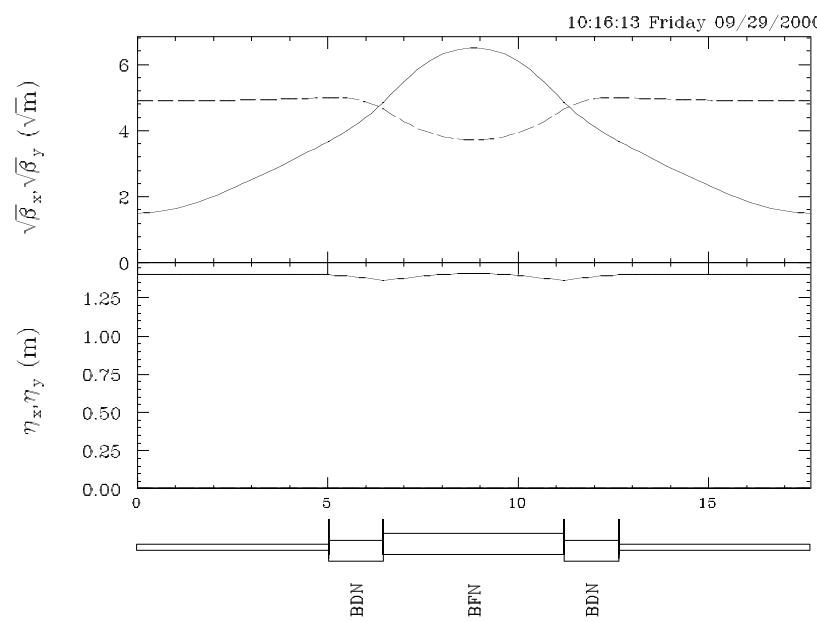
FFAG 1 - 3 GeV

r **30m**
of sector **32**
B field **3.6T**



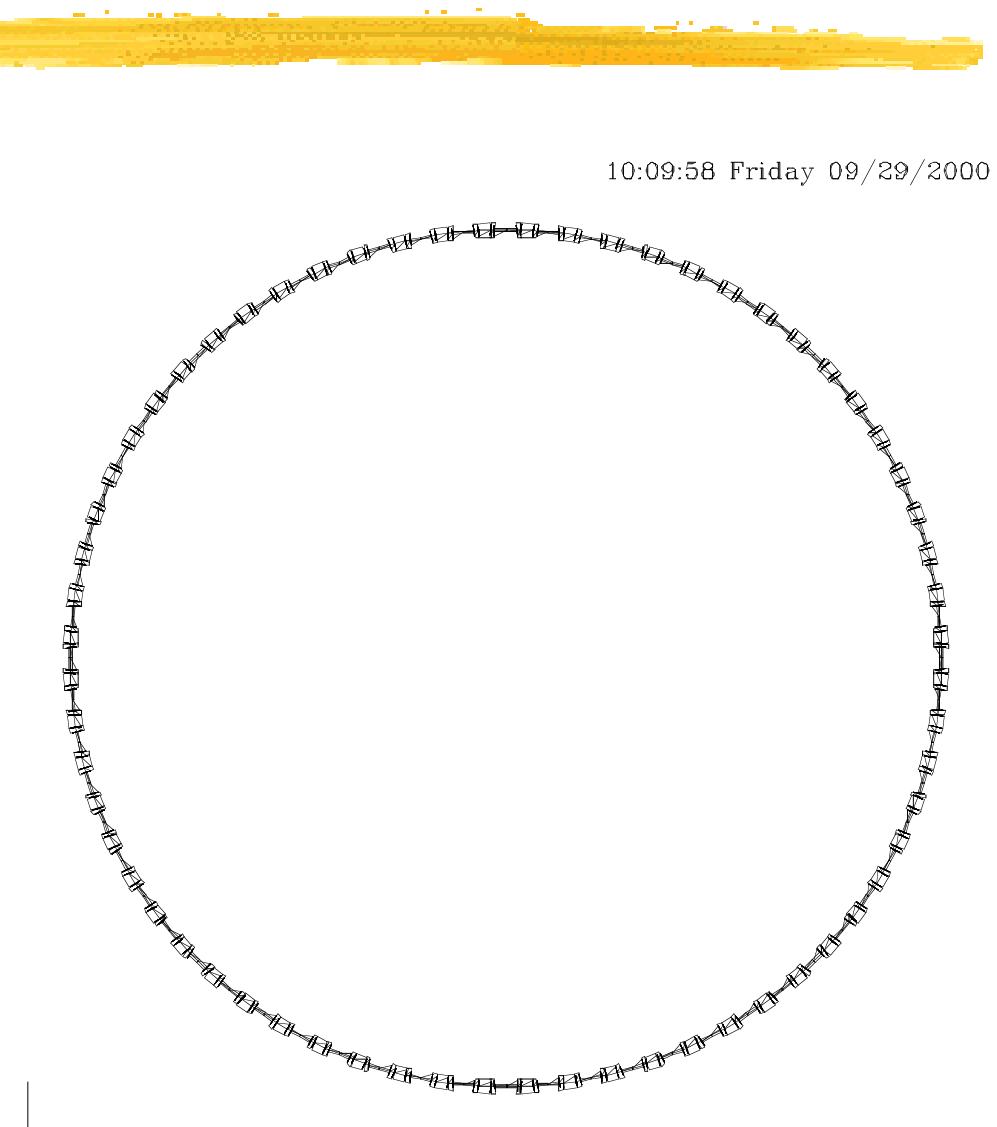
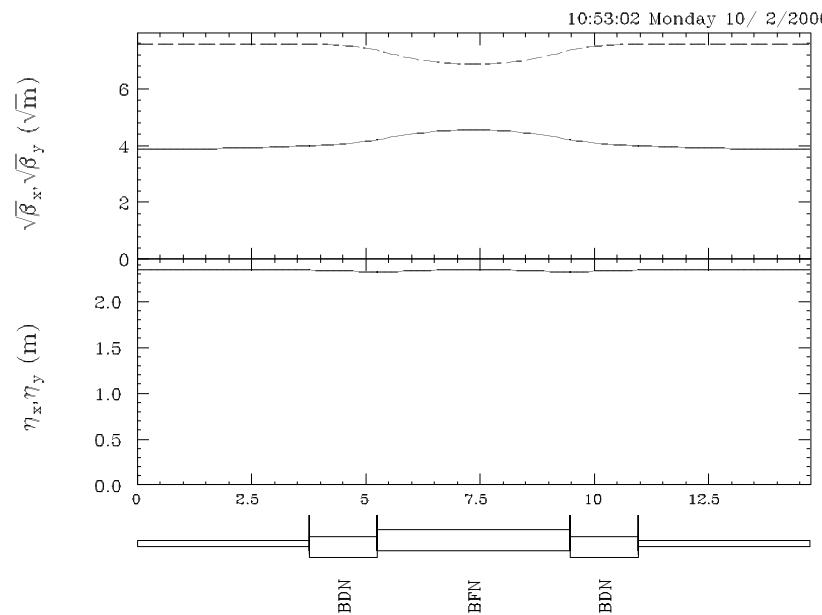
FFAG 3 - 10 GeV

r 90m
of sector 32
B field 4.2T

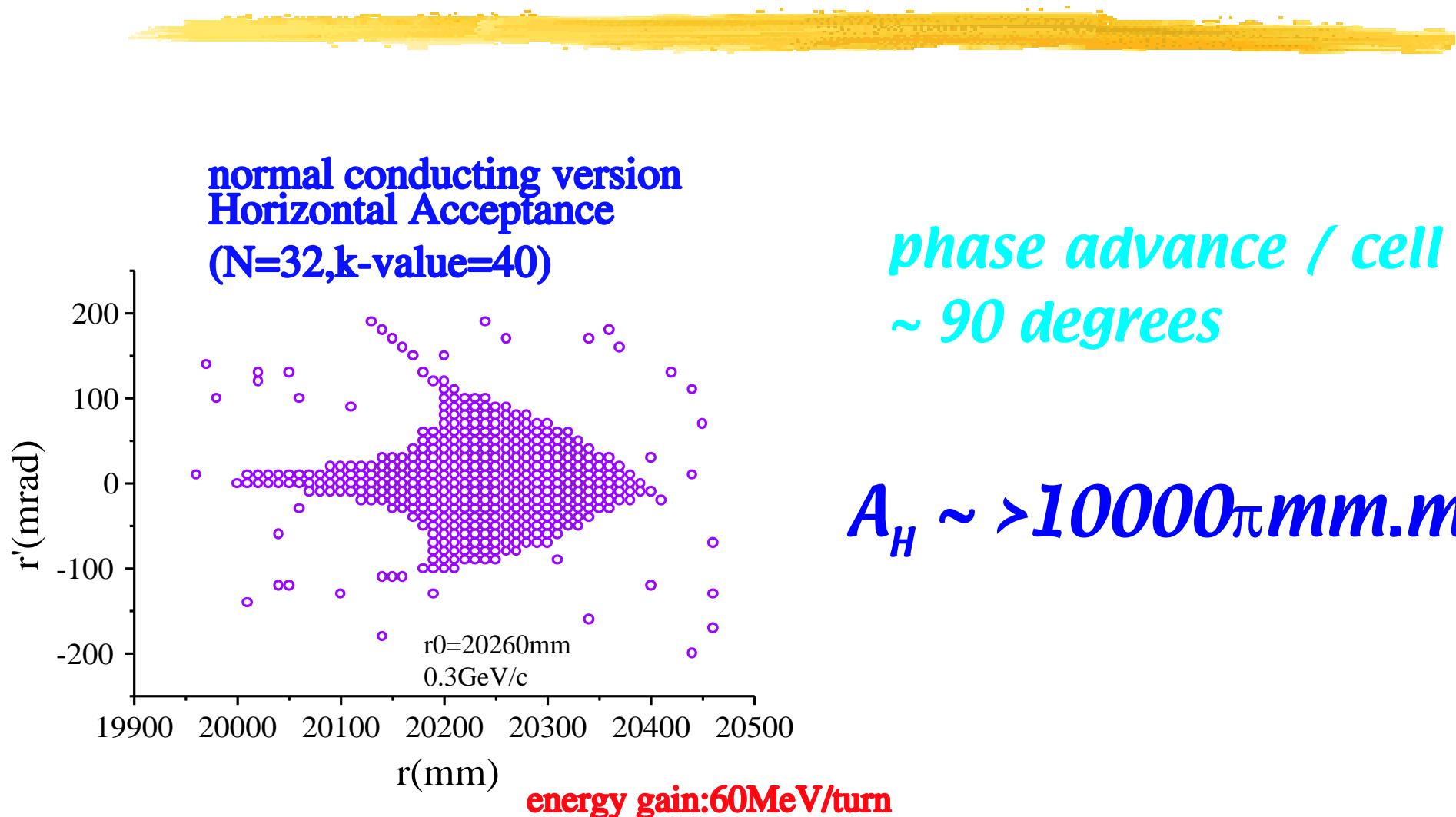


FFAG 10 - 20 GeV

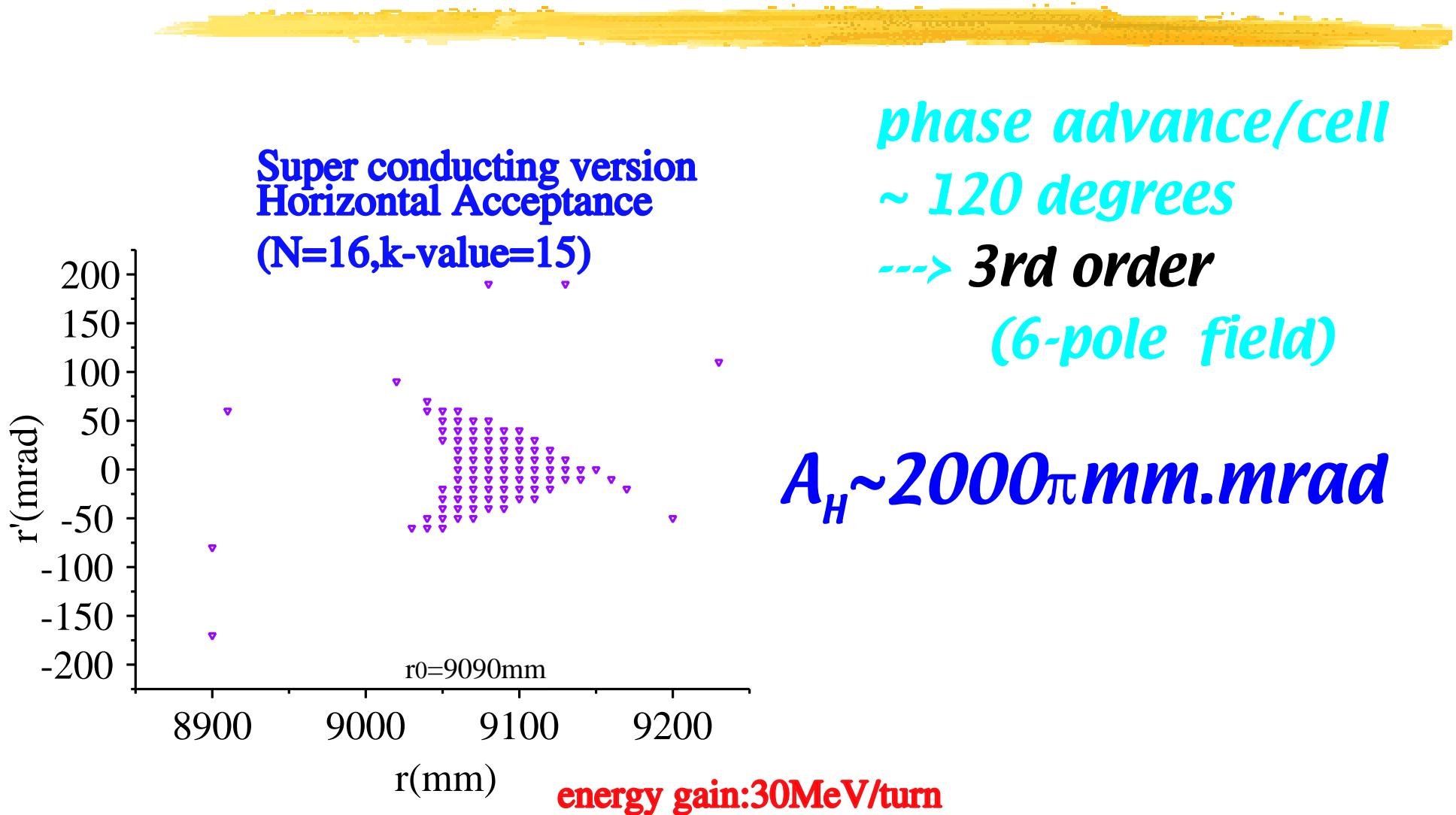
r 150m
of sector 64
B field 5.0T



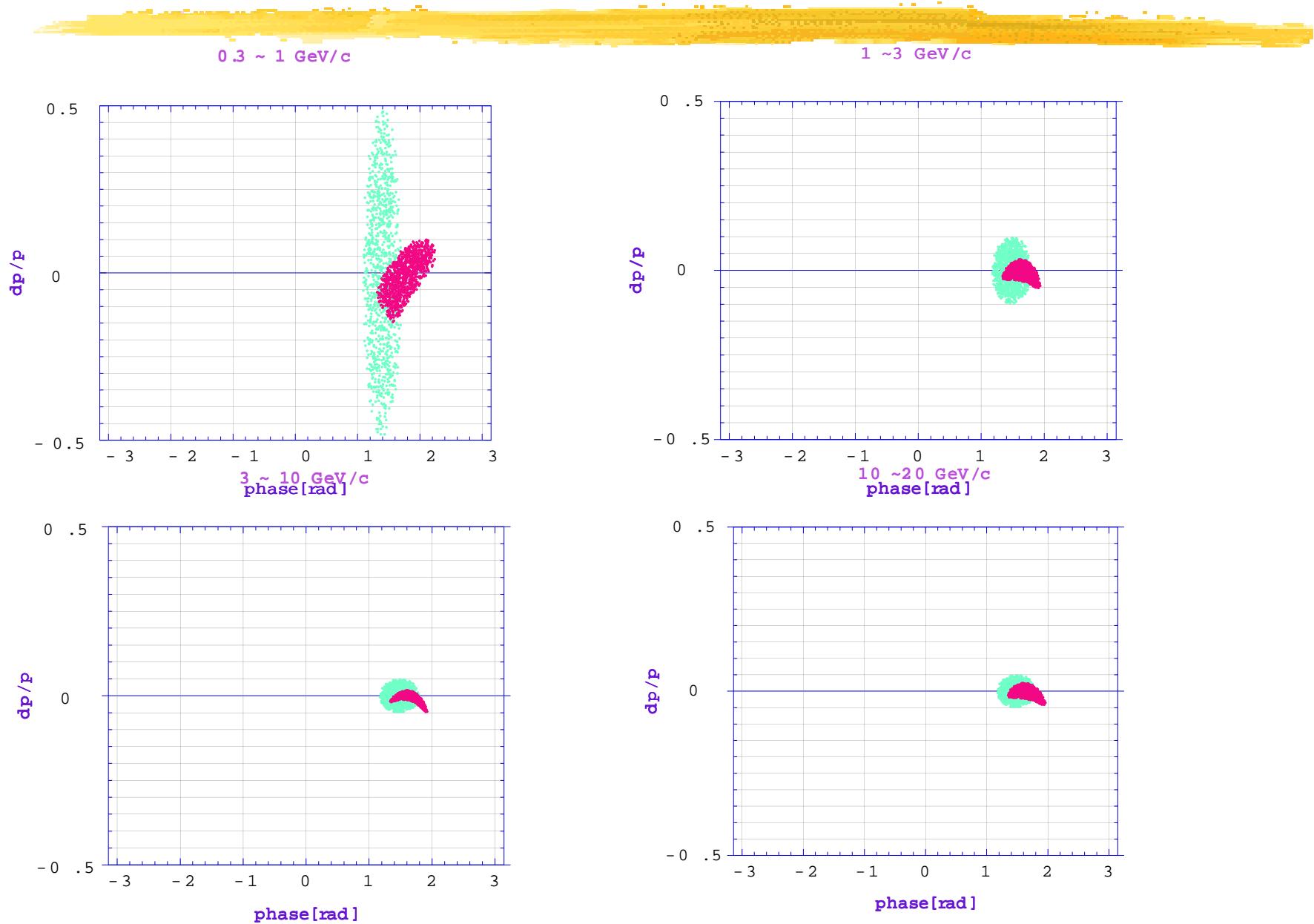
Dynamic Aperture of FFAG ring (0.3-1GeV/c)



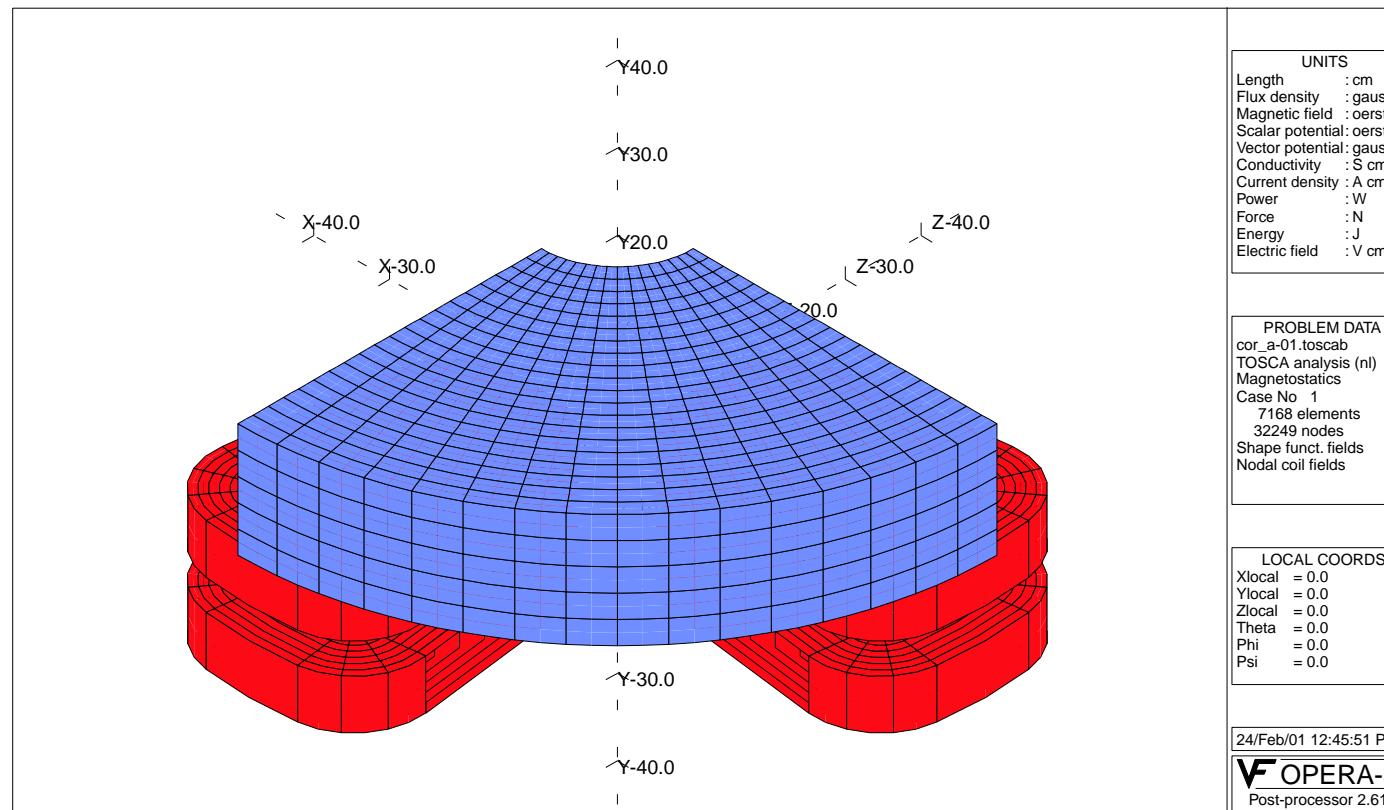
Dynamic Aperture of FFAG ring (0.3-1GeV/c)



Longitudinal motions in the FFAG rings

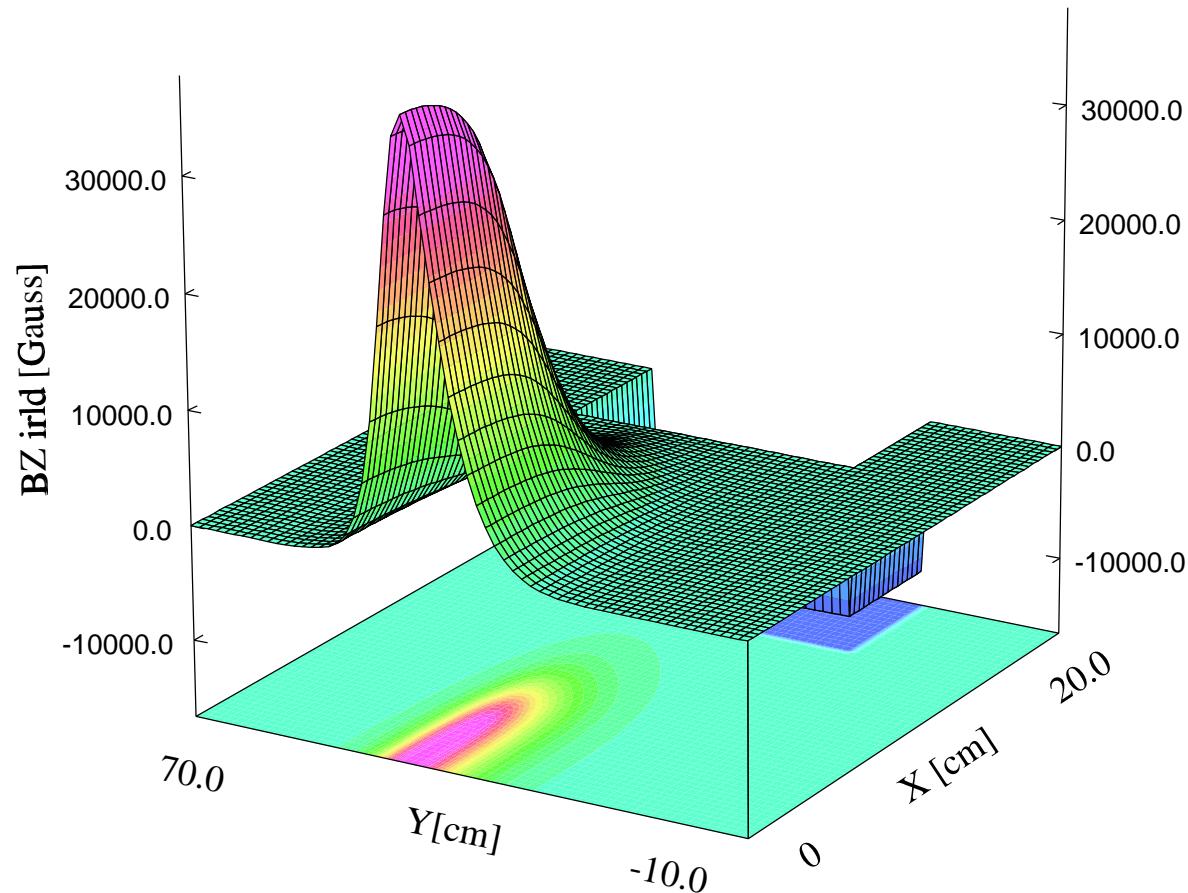


Superconducting Magnet for FFAG

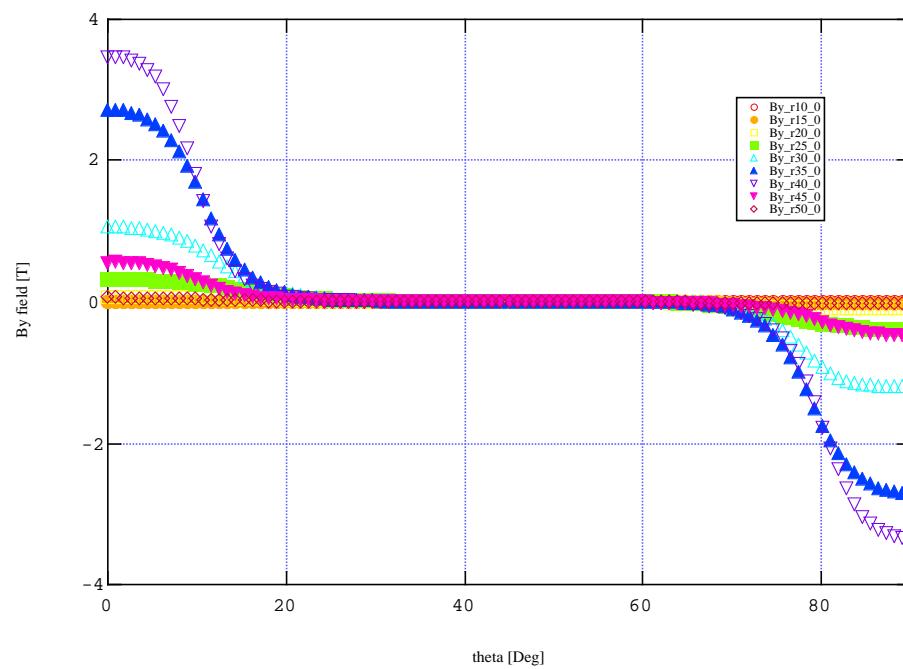


Magnetic field configuration

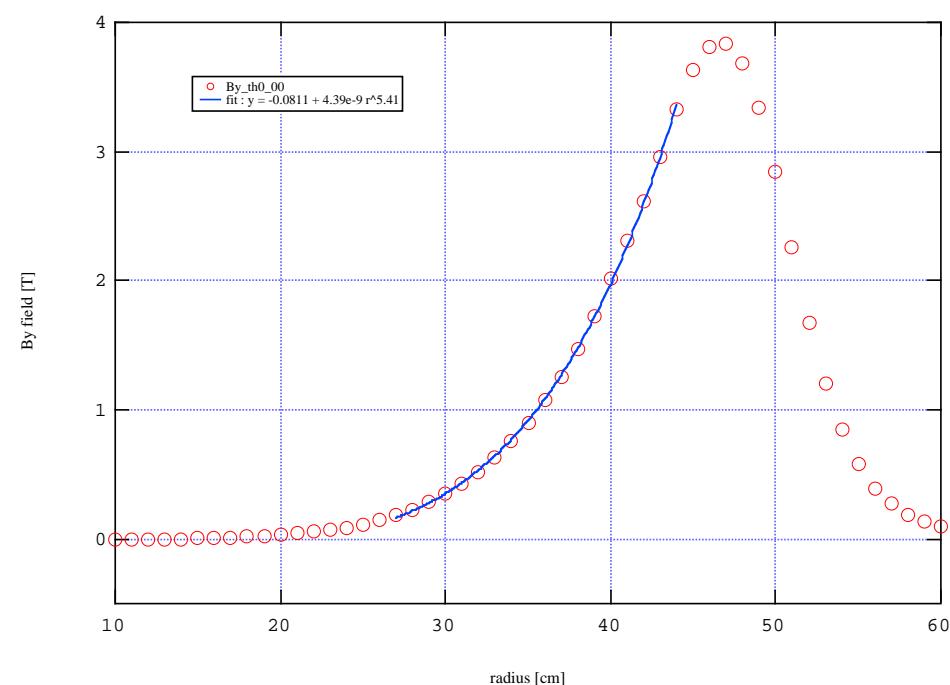
Superconducting magnet



Magnetic field configuration of SC magnet



θ direction



radial direction

Muon Intensity

After Solenoid Capture

~0.3 muons/proton

50-GeV PS

B=20T

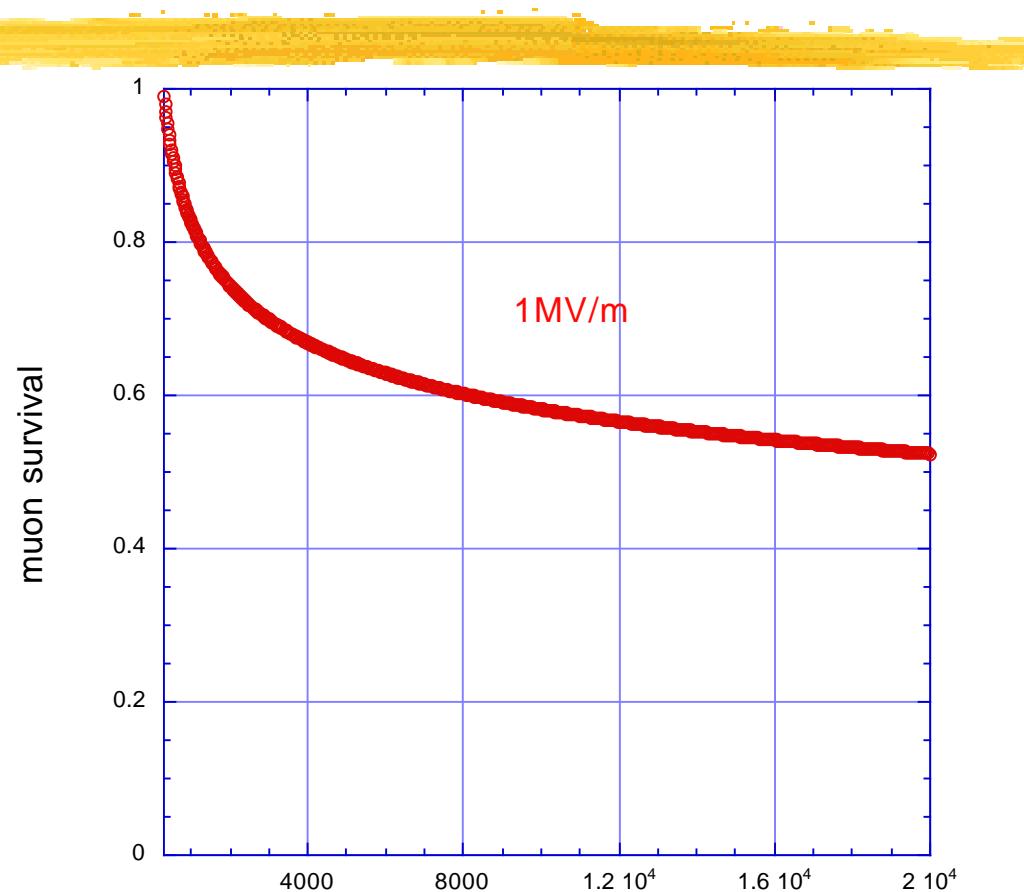
p=300MeV/c

Dp/p=+-50%

A=20,000 π mm.mrad

@P=20GeV/c

I=2x10²¹(p/y)x0.3x0.52x0.3=1x10²⁰ muon decay/y



Summary



FFAG is wonderful !

3rd Wordshop FFAG02 : Feb. 2002 at KEK

<http://hadron.kek.jp/FFAG>